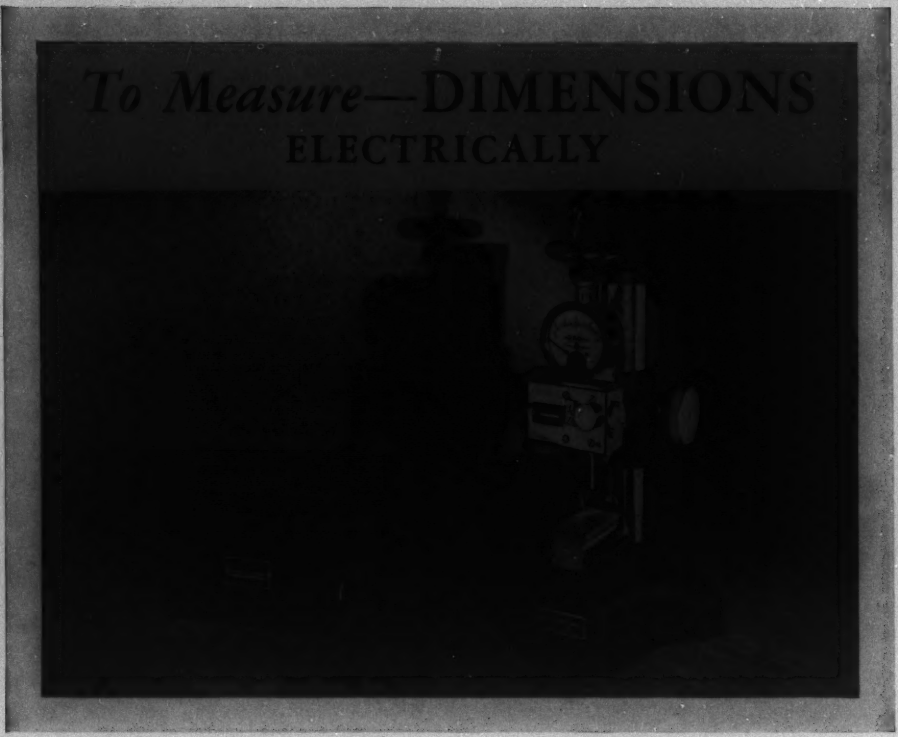
Electrical Engineering

February
1938

To Measure—DIMENSIONS ELECTRICALLY



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4

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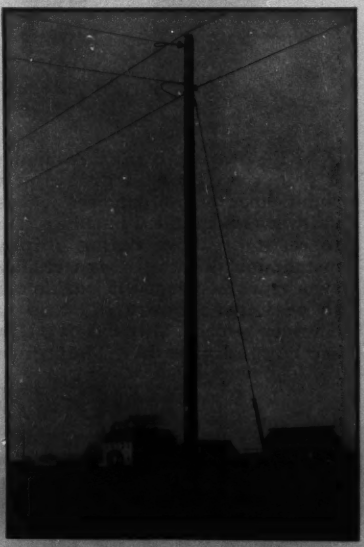

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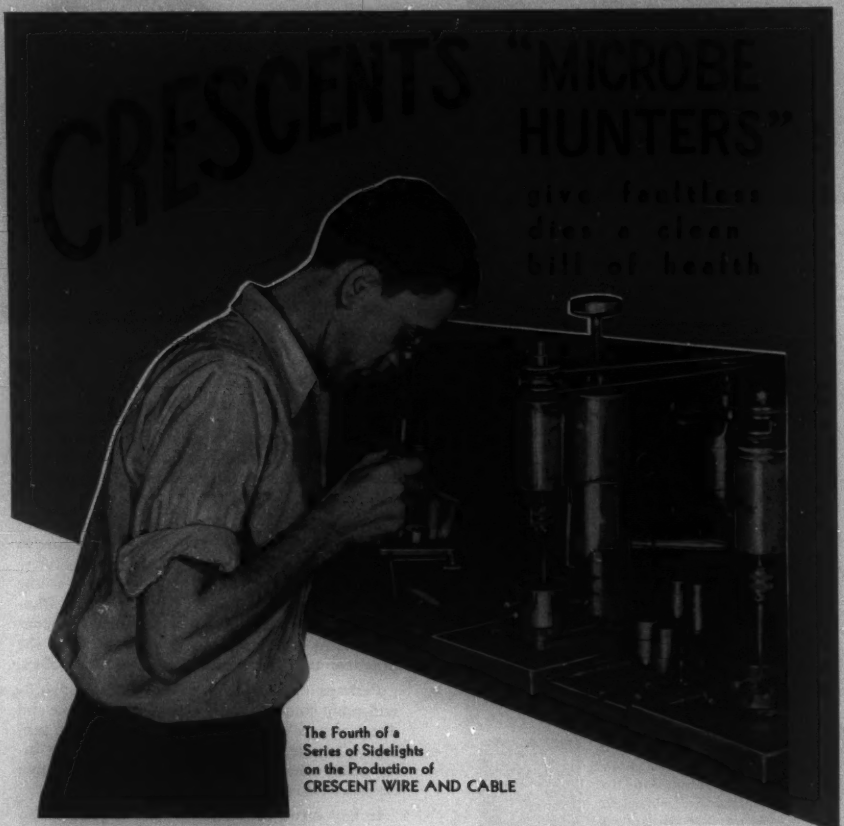

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Electrical Engineering

Registered U. S. Patent Office

for February 1938—

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The Cover

Edison Memorial Tower at Menlo Park, N. J., which will be dedicated soon (*see page 78*).

Photo courtesy
Walter Kidde Constructors, Inc

High Lights

Electrolysis. Electric currents flowing through the earth may cause rapid corrosion and destruction of buried metal by electrolytic action, and steps to control or reduce the damaging effects must be taken in order to protect investments in oil, gas, and water pipe lines, underground cables, and other subsurface structures. Differences of potential may be caused by the contact of various materials, just as in a battery cell, but a serious cause is the grounded track return circuit of electric railways which may produce potential differences in the earth at great distances from the track (*pages 67–77*).

Lightning Strength of Wood. The use of wood for supporting structures in transmission and distribution circuits is as old as the power-distribution art itself, yet little qualitative information on the lightning strength of wood has been available. A paper in this issue presents data on the voltage-time characteristics; polarity effects; and the effects of moisture, age, and creosoting on supporting structures (*Transactions pages 91–101*).

Electricity Aids Accounting. A system of remote-control accounting by electrically operated machines has been tried in a department store for the handling of both cash and charge sales up to a peak transaction rate of 9,000 per hour. By means of sorting and tabulating machines, accurate analyses may be made quickly from the punched cards (*Transactions pages 78–87*).

Tensor Analysis. The tensor, having been caught in the "hunt" conducted through the pages of the January issue, is forced in this issue to reveal many of its secrets. One final chapter remains to be told: In a subsequent issue the reader will be informed of the various useful applications of the tensor in engineering and physics (*pages 61–66*).

Engineering and Economics. Because of the success of the "general session" held during the AIEE 1937 summer convention, a similar session was included on the program of the 1938 winter convention just concluded in New York, N. Y. For the benefit of those not present, full text of the principal address at that session is published in this issue (*pages 51–6*).

American Engineering Council. The 18th Annual Assembly of AEC, "Engineers' Embassy" in Washington, D. C., recently was held in that city. Reports of the work of Council during 1937 were given, also, the annual conference of Engineering Societies Secretaries and "all engineers dinner" were held (*pages 80–1*).

Street Cars. Collective effort has produced a modernized and greatly improved street car that satisfies the requirements of fast acceleration and braking, low noise level, good riding, ventilation, and illumination, and minimum maintenance at a price that appears to meet the economic requirements (*Transactions pages 61–6*).

Matrices. The use of matrices in certain electrical problems recently has attracted much interest; a paper in this issue outlines another application and allows the reader to set up a comparison between the vector-dyadic method and the matrix method (*Transactions pages 74–7*).

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Officers and Committees (For complete listing see pages 1217–21, September 1937 issue)

Network Analyzer. Engineering calculations for complex power system networks may be simplified by the use of network analyzers. A new type of a-c analyzer is described in this issue (*Transactions pages 67-73*).

Faults on Network Feeders. Results of field tests provide some understanding of the magnitude of currents in a secondary a-c network during a line-to-line fault on the high-voltage feeder (*Transactions pages 88–90*).

Industrial Standardization. An outstanding Institute member reflects upon the efficacy of standards in engineering and manufacturing practice, offers suggestions for the improvement of industrial standardization (*pages 57–60*).

Winter Convention. As this issue goes to press, the AIEE 1938 winter convention is being held in New York, N. Y. A detailed report on the convention and its activities is scheduled for the March issue (*page 78*).

AIEE Members Honored. The 1937 Washington Award and the initial (1937) award of the Gaston Planté Medal will go to prominent members of the Institute (*pages 78–9*).

DISCUSSIONS

Appearing in this issue are discussions of the following papers:

Communication

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Electrical Machinery

Carbon Brushes for Steel Mill Equipment—Kalb 114

Power Transmission and Distribution

Distortion of Traveling Waves by Corona—Skilling and Dykes 102

Analysis of Series Capacitor Application Problems—Butler and Concordia 110

Protective Equipment

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Selected Subjects

A Review of Radio Interference Investigation—Sanford and Weise 107

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Technological Development in Relation to Economics

By HAROLD G. MOULTON
President, The Brookings Institution

THE great economic changes of the past 20 years and the accompanying political upheavals have made it increasingly apparent that we are living in the midst of what may be called an era of profound historical change, the ultimate consequences of which no one can now foresee. It is therefore incumbent upon us as the inheritors and transmitters of civilization to study in as fundamental terms as our intelligence makes possible, the nature of and the reasons for the business, economic, engineering, and political problems and tendencies which are shaping our fortunes and our destinies. Whether our individual activities are devoted to manufacturing, mining, farming, banking, trade, or the professions, we all are vitally affected by current trends and all interested in having a more efficiently functioning economic system.

The simple truth is that we are all interested in a common goal, namely, that of higher standards of living for the population as a whole. This is true whether one is pleased to classify himself as radical, conservative, liberal, New Dealer or Old Dealer, Republican, Democrat, Socialist, Communist, or Fascist. Our disagreements relate almost entirely to the methods by which the desired goal is most likely to be attained. The differences which exist here arise in the main out of differences in knowledge and understanding with respect to the forces and factors which control the operation of the economic system.

The problem before us is of course of special interest to engineers. Traditionally, the engineer properly has looked upon his profession as of fundamental importance in the larger scheme of things. It has been through engineering that the great discoveries of science have been made available for the service of society and in consequence, the function of the engineer has sometimes been extolled almost to the exclusion of other contributing factors in economic progress. But the events of the last decade have given rise to a baffling situation for the engineering profession. Reference is here made, not only to the slackness of employment at present, but to an apparent damming up of the whole process by which engineering knowledge is transformed into productive energy. To quote from the Westinghouse Commemoration of December 1, 1936: "The engineer is on the defensive in justifying his work and establishing himself as a constructive element in civilization and a driving force in providing for the well-being of mankind."

More significant still, science itself is facing a question mark. Have we made too many scientific discoveries and is it becoming necessary to halt the advance of science? Some of our most eminent scientists are asking whether, as the years pass, science will continue to be a beneficient power advancing the welfare of society or whether it may prove a sort of Frankenstein monster which may ultimately destroy civilization.

Relations Between Engineering and Economics

Under these circumstances, it is, of course, of the utmost importance that engineers and economists meet in full and free discussion. Engineering and economics are concerned with closely related phenomena. Engineering deals with the application of scientific knowledge to the processes of wealth production. Economics deals with the basic resources and factors upon which wealth production depends and with the forces and institutions which influence or control the operation of what we call the economic system. It is readily apparent, therefore, that the advance of engineering has a vital bearing upon economic progress, and that in turn the operation of the economic system largely determines the rate at which new engineering developments may be applied in the actual production of wealth.

The engineering attitude with respect to economic progress has always been direct and fundamentally simple. Moreover, its validity is not open to challenge. It is based upon the elementary assumption that the function of engineering is to apply the new knowledge that is continuously accumulating, to the improvement of productive instruments and processes, with a view to increasing the efficiency of mankind in adapting natural resources to the satisfaction of human wants. Increasing efficiency simply means producing more with the same effort, in consequence of which standards of living will or should be raised.

If it be agreed that the engineer's conception of progress is indubitably true, it must follow that the test of an economic system is to be gauged by its efficiency in promoting the engineering ideal. The system of private business enterprise, as it has often been expounded both by professional economists and business and other leaders, does in fact embody this engineering conception of progress.

The nature of the problem is, however, complicated by the fact that under the capitalistic system, production is carried out through financial or pecuniary processes. Business managers use money in the hiring of labor and in the purchase of materials and supplies and they sell their

An address presented January 26, 1938, at the "general" session of the AIEE winter convention, New York, N. Y. Reprints available upon request.

HAROLD G. MOULTON received the degree of doctor of philosophy from the University of Chicago in 1914, and was a member of the faculty until 1922. At that time he resigned the post of professor of political economy to become director of the Institute of Economics, Washington, D. C. The institute was amalgamated with the Institute for Government Research and the Robert Brookings Graduate School of Economics and Government in 1927, and Doctor Moulton was appointed president of the newly formed Brookings Institution. He is the author of many books on economic and allied subjects.

products for money. The aggregate amount of money received from sales must, of course, exceed the aggregate costs if profits are to be realized. Thus, business and in turn engineering, has its setting in a structure of monetary costs, prices, and profits; and the economic requirements for progress must accordingly be analyzed in these financial or pecuniary terms.

Mechanisms of Capitalism

The incentives and mechanisms by which the competitive system has been imposed to ensure rapid economic progress and higher standards of living may be briefly summarized as follows:

First, it is contended that each business manager naturally stands to gain by increasing efficiency and thereby reducing costs. He may accomplish this by the construction of a larger and more efficient plant; by the installation of better equipment; by the introduction of superior internal management; by improved methods of marketing; or by a combination of these various methods.

Second, having reduced costs of production, he is in a position to increase his profits in one or the other of two ways. He may continue to sell at the same prices as before, enjoying the advantage of a wider margin between cost and selling price, or second, he may expand the volume of his business by means of price concessions. It was reasoned that since the increase in efficiency, which is responsible for the reduction in costs, commonly involved an expansion of productive capacity, and since the maximum economies can be attained only when operating at full capacity, the greatest profit will result if sales are expanded by means of a reduction of prices. In short it was held that increased efficiency makes possible lower prices, while the profit incentive insures an actual reduction of prices.

Third, the profession naturally involves the elimination of obsolescent or otherwise inefficient high cost establishments. The industrially fit, as gauged by an ability to sell at a minimum price, alone survive. Moreover, the efficient of today promptly become the inefficient of tomorrow. A particular businessman, firm, or corporation may indeed survive over a long period of years, but only if the production methods employed keep always abreast of changing times.

It will be seen that with a system thus operating, standards of living would steadily rise. The progressive reduction of prices as efficiency increases would, of course, constantly expand the purchasing power of the masses, giving them an increasing volume of goods for the same money.

It should be carefully noted that this theory of progress implies that a reduction in money costs must result from increased efficiency rather than from a mere reduction in hourly wage rates. A reduction in wage rates may indeed lower money costs and prices but since it increases neither efficiency nor the purchasing power of the masses, there is no resulting advancement.

The Degree of Recovery

At the present moment, our minds are naturally focussed upon the new business reaction which began in the early autumn of 1937. Every one is asking whether we are in for another major depression comparable to that which began in 1929, or whether we are confronted merely with a period of minor readjustment. I am not interested in forecasting the fluctuations of the stock market or the duration of the present depression. Political and other factors play so powerful a role in these days that it is impossible for either economist, statistician, or business seer to foretell with any certainty the outcome of current trends.

It is possible, however, to throw light on the sources of maladjustment responsible for present conditions and thus in some measure to make clear the requirements for enduring economic progress. As a foundation for our thinking, let me first indicate the degree to which recovery from the world depression of 1929–1933 has been achieved.

This can best be done by reference to the figures of per capita production and income at the present time as compared with 1929. The income produced by the American people in 1929 aggregated about 81 billion dollars, which is equivalent at 1936 prices to approximately 72 billion dollars. Now, in 1936, the aggregate production was about 64 billion dollars or approximately 90 per cent as great as that of 1929. Preliminary estimates for 1937 which were made in October before the full magnitude of the current depression had become clear, indicate a rise to approximately 69 billion dollars; but more than half of this increase is attributable merely to the rise of prices in 1937.

In comparing these figures with 1929, it must moreover be borne in mind that a smaller percentage of the total income is now derived from the productive activities of private enterprise. Government disbursements, including work relief and agricultural benefit payments, stood in 1936 at over 9 billion dollars as compared with 6 billion dollars in 1929, an increase of about 3 billion dollars. The proportion of the total national income disbursed through government channels, representing enterprise in the main that is not of a tax-paying variety, increased from 8 per cent in 1929 to 14.6 per cent in 1936. Thus, in terms of real goods and services, current income figures somewhat overstate the situation for purposes of comparison with 1929.

It is necessary to bear in mind also that since 1929 the population of this country has increased approximately six per cent and the population of working age by nearly 10 per cent. In *per capita* terms, accordingly, the present national income is less than 85 per cent that of 1929.

Even this figure does not reveal the full extent to which our position has deteriorated since 1929. In our production of consumption goods, where we have attained most nearly to predepression levels, we have been continuing to use plant and equipment constructed before 1929, much of which has deteriorated or is of an obsolete pattern and is in serious need of replacement in the interests of productive efficiency. Accordingly, if we are to restore standards of living to the predepression level or higher, we must, in order to make good these accumulated deficiencies, have a level of production for some years to come substantially above that of 1929, while we are making up these arrearages.

Production Requirements

The production task before the people of this country may be stated then in the following terms:

First, to make good the actual deterioration of plant and equipment, sustained during the depression. Second, to increase produc-

tive capacity in proportion to the growth of population that has occurred. And third, to expand the output of consumption goods in accordance with this growth of population.

Popular thinking centers mainly on the last of these requirements, that is, the increase of consumption goods. But the achievement of this goal depends fundamentally upon the fulfillment of the first two requirements; namely, making good the deficiencies of plant and equipment resulting from seven years of subnormal replacement, with depreciation and obsolescence continuing, and also expanding the rate of capital growth in proportion to the rate of population growth that has already occurred.

We recently have made, at the Brookings Institution, a comprehensive analysis of the expansion of output that would be required in the next few years to restore former levels of production and consumption. (Published in "The Recovery Problem in the United States.") We set it as our task to determine how great an increase would be required to restore by 1941, a per capita production and consumption merely equal to, not better than, that of 1929. We set this problem up in engineering, as distinguished from economic, terms. We were not concerned with analyzing for the moment whether it was going to happen or not, or in analyzing the forces and factors which would govern the rate of progress in the next few years. We set the problem up solely in terms of requirements.

We studied in turn the situation in the fields of housing, passenger automobiles, other durable consumer goods, steam railroads, public utilities, and industrial and commercial enterprises. Each of these studies involved taking account of the restricted rate of replacement during the last seven years and the requirements also resulting from the continued growth of population. Taking the whole field of durable goods into account and stating the results in aggregate terms, we found that the volume of production over the five years from 1937 to 1941, inclusive, would have to be roughly 60 per cent greater than it was in 1936, and approximately one-third greater than it was during the boom period of 1925 to 1929. Stating these requirements in terms of dollars, we did produce in the field of these durable goods in 1936, about 21 billion dollars' worth; (that is, out of that 64 billion dollars' worth of goods and services, about 21 billion dollars was in the field of durable goods). We would have to produce instead of 21 billion dollars annually over the next five years, about 33 billion dollars' worth, if we are to restore living standards to the level of 1929.

The primary explanation of these enormous production requirements to get us back to where we were is, of course, to be found—and I emphasize this again because it is so commonly and so universally overlooked—in the continuing rate of population growth on the one hand, and the suspended rate of growth in productive capacity on the other. A depression has comparatively little effect upon the rate of growth of population but it has a profound effect upon the rate of growth of producing capacity. The real costs of our great depression in social and economic terms are registered in these fundamental changes in relations. They can be overcome only through a rebuilding process which first will make good the positive deficiencies and then expand productive capacity in proportion to the growth of population.

The increase in productive efficiency during the course of the depression years has not been sufficient to offset our failure to increase the supply of productive capital. While there has been a substantial advance in man-hour productivity in manufacturing industries, the same has not been true to anything like the same degree in other lines of production. For the economic system as a whole, the increase in man-hour efficiency is, according to our studies, much less than ten per cent.

Labor Requirements

Meanwhile, with a view to solving the unemployment problem, we have been rapidly reducing the length of the working week. A contrast will help to illuminate the significance of recent trends. During the period of great technological progress from 1900 to 1929, the length of the working week in the United States was reduced on the average by about 13 per cent. During this generation, the per capita production moreover expanded by nearly 40 per cent. Thus, the American people were receiving the benefits of technological improvements largely in the form of more goods and services, though partly in the form of greater leisure. But during the period from 1929 to 1936, with productive expansion held in check by the forces of depression and with our per capita production reduced by more than 15 per cent, the working week was reduced approximately 20 per cent below the 1929 level. We have more leisure but fewer goods with which to enjoy it.

It will now be of interest to consider the labor requirements for carrying through the program of expanded production that is necessary to restore living standards. There is a widespread belief that somehow or other we must continue to reduce working hours as the only possible means of providing employment for our entire working population. Our investigations indicate that in the field of capital goods and durable consumer goods, from eight to nine million additional workers would be required annually over the next five years to carry through that production program which I outlined as constituting the minimum requirement for a restoration of former standards of living. In nondurable consumer goods, the increased production and labor required would, of course, be very much less because the curtailment of production in these lines has been very much less than in the field of durable goods. There can be no doubt, however, that the work requirements to restore living standards during the next five years are more than sufficient to absorb the entire volume of unemployment now existing.

The simple truth of the matter is that we have not yet reached a stage of technological development at which it is possible for the American people to attain the standard of living which they desire with working time as short as that which now prevails in American industry generally. Bear in mind that the estimates of production which I have here presented have assumed a return merely to 1929 levels. What we need, of course, is much higher levels than these if we are to have a standard of living to which we aspire. Our research reveals that anyone who favors a further general reduction in the length of the working

week at this stage of our economic development is unwittingly favoring lower standards of living.

Wage and Price Relationship

Thus far in this analysis, it has been confined to a statement of facts as to what is required in restoring standards of living. Attention must now be shifted to certain forces or processes involved in the operation of the economic system. The economic system, or machine, as I prefer to call it, is one of great complexity, the successful operation of which depends upon the maintenance of a balanced adjustment among the various parts.

Time does not permit a consideration here of all the factors entering into a satisfactory adjustment of the economic system. Attention will be focussed upon the relationship of prices and wages, to which I have already alluded, because it is here that we find at the present juncture the primary source of difficulty.

Business activity involves the sale of goods in the market for money and the disbursement of the income accruing to those who participate in the productive process in the form of money—as wages, interest, profits, and so forth. The successful operation of this system requires adherence to two fundamental principles.

First, *the process of raising the standards of living of wage earners necessarily involves increasing the ratio between wage rates and prices.* If the wage earner gets more dollars and prices remain unchanged, his purchasing power is expanded. If he gets the same number of dollars and prices decline, his purchasing power is expanded. But it can be expanded only by increasing wages in comparison with prices.

Second, *an increase of wage rates relatively to prices depends fundamentally upon increasing the efficiency of production.* Only thus will the means be available with which to pay higher real wages and provide more goods and services. Accordingly, there must be a constant acceleration of technical advances, improved management, increased labor efficiency, and so forth. Any practices or policies that tend to work in this direction may be regarded as economically sound, and any that tend to work in the opposite direction must be pronounced economically unsound.

Now, it is this second principle—and let me emphasize this with all the power at my command—that is so commonly overlooked in all public discussions of wages, prices, and purchasing power. Attention has been concentrated upon increasing the flow of *money* income: first by reducing the number of hours worked, thereby increasing the number employed; and, second, by raising the rates per hour. Little thought has been given to the increase in productive efficiency and productive output which alone make higher real wages possible.

With these principles in mind, I want now to review the course of the recent recovery movement. During the summer of 1933, wage rates were sharply increased as a result of the code agreements under the NRA. Prices advance quickly but not quite proportionately. Then from 1934 until the third quarter of 1936—please note these dates carefully—from 1934 until the third quarter of 1936, wage rates continued to increase at a moderate pace while the prices of manufactured goods remained practically stable. Now, during this period productive efficiency was materially increased—in fact, in rough proportion to the increase in wage rates.

The economic results of these trends were as follows: One, the increase in productive efficiency and the fuller utilization of plant capacity resulted in lower unit costs. Two, the increase in wage rates as compared with prices, steadily expanded the purchasing power in real terms of employed industrial workers. Three, the expanding volume of sales led to increased profits, the reduction in unit costs more than offsetting the increase in wage rates.

Changes in 1937

The trends up to late 1936 were thus distinctively favorable from the standpoint of these relationships. Production was steadily expanding and unemployment decreasing. Purchasing power was being broadly disseminated among the masses. Speculative business activity was not strongly in evidence and the general balance between current production and current consumption appeared reasonably satisfactory, and if the existing favorable balance could have been maintained, there was good reason for hoping that we might be entering upon a period of exceptional prosperity that would in a few years go far toward restoring the economic losses resulting from the depression.

It was apparent at the end of 1936, however, that forces were at work which threatened the equilibrium between wages and prices. In an address before the National Association of Manufacturers in December 1936, I made the following statement:

> "The generally favorable price situation appears to be in imminent danger of succumbing to pressures and temptations inherent in the immediate situation. In the last quarter of 1936, tendencies have developed which threaten a reversal of recent policies. Increases in taxes, rising prices of important raw materials, and demands for further substantial increases in wages are exerting a powerful pressure in the direction of rapid price advances. These are very real forces, perhaps irresistible."

In the first quarter of 1937 came the development primarily responsible for destroying the existing balance and altering the whole course of events. I refer to the aggressive labor movement which succeeded in obtaining for a large part of American workers a substantial reduction in the length of the standard working week and substantial advances in rates of pay.

Now whereas the gradual increases in wages during the preceding three years had been accompanied by roughly proportional increases in efficiency, the sharp advances of 1937 were wholly unrelated to efficiency. Indeed, the accompanying industrial warfare meant inevitably a decrease in efficiency for the time being. Hence an advance in prices appeared necessary if profits were to be maintained. Amid the stress, confusion, and fear that existed, prices were rapidly advanced, and a vicious spiral of rising costs, rising prices, and further increase in costs appeared in prospect. This situation was, of course, conducive to advance purchasing and the accumulation of inventories.

In the light of these wage and price advances, I wrote in April [1937],

"Developments such as these produce serious maladjustments in the economic system as a whole. Particular labor groups which receive higher wages may stand to gain for a time. Similarly, the industries involved may temporarily pass on the higher costs to consumers. But further extensive expansion appears definitely to be menaced by this inflationary process. The advance in the prices of such basic products as iron, steel, other metals, and building materials, may impede expansion in certain important lines. The financial condition of the railroads has only recently improved sufficiently to promote extensive physical reconstruction of properties; but now, with steel prices rising rapidly and railway wage increases in prospect, it is doubtful whether the railroads will be able to carry out the needed programs of rehabilitation. Similarly, the rising prices of building materials may hold in check the building of new houses and apartments."

Comparison of Wage and Price Advances

Before proceeding further, we must look at the significant figures as to wage and price trends since the autumn of 1936. Hourly earnings—as computed by the United States Bureau of Labor Statistics for all manufacturing industries—increased between the third quarter of 1936 and the second quarter of 1937 by approximately 16 per cent. The wholesale prices of finished products rose during the same period a little over six per cent, or only a little more than one-third as much as hourly wages. In some lines, of course, the price raise was much greater, notably in iron and steel, where the advance was about 12 per cent. However, the wages costs in this industry increased about 25 per cent. Current published statements on this issue have been highly misleading because in indicating the increase in wages they take account only of rates and make no allowance for the shortening of working hours and extra pay for overtime.

Industrial production increased between the third quarter of 1936 and the second quarter of 1937 only a little, the index number rising from 115 to 117. Meanwhile, however, profits in manufacturing industries did not suffer. This is because an increase in prices proportional to the rise in wage rates was not necessary in order to maintain profits, since wages constitute only one item in the list of costs. The fact is that in the second quarter of 1937, the index of earnings of 120 industrial companies was 5 per cent above the excellent fourth quarter of 1936, and 20 per cent above the level of the first quarter of 1937. One must conclude, therefore, that so far as manufacturing industries were concerned, the price advances were somewhat greater than was necessary to maintain existing profit margins.

Effects Upon Other Industries

With railroads and public utilities the story was entirely different. The rising costs here could not be passed on in the form of increased prices immediately. Hence, profits were adversely affected almost instantaneously. Railroad earnings dropped nearly one-third in the second quarter of 1937 as compared with the last quarter of 1936, and public utility earnings declined by about 14 per cent. Subsequent wage increases, justified by higher living costs, have further complicated the railroad situation and set the stage for an insistent demand for higher rates as the only hope of forestalling another breakdown of the railroad financial structure. It is by no means certain that higher rates, particularly at this juncture, would accomplish the desired purpose.

In a similar way, sharply rising costs and prices have pinched the housing industry and arrested the vitally needed expansion which was just beginning to get under way. Despite the need for housing, rents had been rising but slowly. Hence with the advance in building material prices and wages, the profit margin was again reduced and building commitments again lagged.

Meanwhile, also, because of increasing evidences of domestic maladjustments of the kind mentioned and of crises abroad, the stock market turned first pessimistic and then panicky. With the tragic losses of 1929 fresh in mind, the attitude became, "Let's get out before its too late."

In turn, the decline in stocks warns of troubles ahead and halts business commitments for the future. At the same time stock-market losses necessitates the direct curtailment in some measure of luxury expenditures and also they embarrass in some degree normal business operations. The accumulation of inventories while prices were rising obviates the need of quick replacements and hence the flow of orders declines. Thus business recession begins and spreads through the countless interactions in the delicate web of industrial interrelations.

The factors responsible for checking the expansion movement, checking it long before we had recovered from the destructive effects of the last depression, can thus in this instance be definitely traced. The only element of surprise was the rapidity with which the succession of events brought the business reaction. Early in the year, it seemed possible that the purchasing power of ultimate consumers might be so large as to offset the adverse effects of disruption occurring elsewhere and insure large activity for the balance of the year. It should be pointed out in this connection that during the first half of 1937 with wages up some 15 per cent, the cost of living index, which is based on retail prices and includes rents, was less than 3 per cent higher. Thus for the time being the purchasing power of labor was substantially increased, while that of nonwage earners was reduced only a little. Indeed, farm income was higher. That was due to favorable crops and good prices in the United States as a result of crop failures elsewhere. Despite the increase in purchasing power among the masses of consumers as a whole, the break came quickly—more quickly, I am frank to say, than I had anticipated.

Political developments, also, appear to have played a role of no small importance. It is significant to note that the recovery movement in the United States lagged as compared with that in other countries during 1934 and the first half of 1935. It was not until the dollar had been stabilized for more than a year and not until the NRA was abandoned that confidence increased sufficiently to promote a really strong advance. There is abundant evidence—though not of a statistical character—pointing to a revival of business uneasiness in 1937 in respect to

government policies. While by no means a direct cause of a maladjustment to which I have referred, once recession had begun this uneasiness served to intensify the all-persuasive gloom.

The Problem of Readjustment

Looking forward to the future in the light of the recent past, we may, I think, define with some clearness the requirements for returning prosperity. There must be a reversal of the trends which produced the maladjustment of 1937.

In thinking of this problem, it is necessary to distinguish between such changes as might be required to bring about renewed activity confined to the field of consumption goods and those needed for the rehabilitation of the capital-goods industries, without which there can be no real recovery of living standards. Recovery in the consumer-goods industry may be brought about, at least in substantial measure, by such factors as the working off of excess inventories and the decline in the prices of raw materials; and the process might possibly be stimulated by an expansion of government spending.

The extraordinarily sharp decline in production schedules while consumption was continuing at somewhere near normal levels has been a favorable factor in that it has made for a rapid reduction in accumulated inventories. Already in some lines the inventory situation appears definitely improved. Similarly the sharp reduction in raw material prices that has occurred should be of genuine benefit to manufacturing industries.

In this connection it is important to note that during the recent recovery movement from 1933 on, raw material prices remained relatively low as compared with the prices of finished products until the second half of 1936, when they rose sharply as a result chiefly of war programs and international speculation in such materials.

In December, 1935, the raw material index stood at 77.3 as compared with the manufacturing index of 82.8, or five points below. In January, 1937, the figure was 88.8 for raw materials as compared with 85.6 for manufactured products. But at the end of the year, in December, 1937, the index for manufactured goods remained practically unchanged at 85.4, while the raw materials index had dropped back from 88 to 75, or below the level obtaining throughout the year 1935. This decline of 15 per cent is of great importance. Meanwhile, some readjustments in wage costs are occurring and undoubtedly an increase in efficiency is accompanying the clearing of the atmosphere in the field of industrial relations. It is thus by no means impossible that a substantial increase in productive activity in the field of consumer goods might come in the course of the next few months. I do not pretend to know, but it is possible.

More thorough-going changes, however, are necessary before expansion in the field of capital goods can occur. Some reductions in wages, coupled with further increases in efficiency, appear indispensable to an expansion of production in some of the more important fields where these maladjustments have occurred, such as housing, where high wage rates defeat labor's objective of a high annual income. In other lines such as public utilities, the wage cost factor is apparently not of such decisive importance.

In general, expansion in the field of capital enterprise, involving long-term commitments, awaits the re-establishment of confidence with respect to the future of the capitalistic system.

This is where government policies touch the economic situation so vitally. If there seems to be a real possibility that we are to embark upon a new and intensified federal program of governmental regulation and control, the objectives of which appear ill-defined and in some measure contradictory, we cannot expect the risks of expanding enterprise to be assumed either by business enterprises in quest of profits, or by individual investors looking for the employment of their savings.

If the political skies could be cleared and agreements be reached with respect to a comparatively few major issues, the foundations would be laid for a period of remarkable economic activity in the rehabilitation of plant and equipment and in the expansion of new capital and durable consumer goods in line with the growth of population and with the companies' consumptive requirements.

The immediate outlook is thus shrouded in uncertainty. There are obviously such conflicting trends and political and psychological influences that no one is warranted in making confident prediction with respect to the next few months. Thus I leave discussion in terms of requirements and merely express the hope that a growing recognition of underlying necessities in the situation, a growing sense of economic reality, may serve gradually to promote the generally higher standards of living which are so greatly needed.

Someone has said that "civilization is a contract between the dead, the living, and the generations yet unborn." This means, I take it, that it is incumbent upon each succeeding generation to build constructively upon the foundations reared by those who have gone before, to the end that those who follow us may in their turn be privileged to enjoy a greater heritage.

This ever-advancing goal of a richer and more understanding life is, it would seem to me, most likely to be progressively realized by evolutionary processes, by the conservation of those elements of our political, economic and social system which experience demonstrates promote the development of individual talents and capacities, and by the elimination of those which work in the opposite direction.

In periods of great social travail, there is an inevitable tendency to believe or hope that revolutionary changes may quickly usher in the golden age—by some uncanny legerdemain give us a short-cut to the promised land of plenty. Unfortunately, reflection upon the long, long story of human progress and analysis of the underlying requirements for economic advancement afford little support for such dreams. Despite the phenomenal achievements of modern science, of engineering and of business organization, for generations yet to come it will be necessary to be content with something less than the millenium.

Some Fundamentals in Standardization

By FRANK B. JEWETT
FELLOW AIEE

Based upon 30 years of experience in standardization, the reflections presented here suggest the need of open-mindedness and progressiveness in the use of industrial standards. Industrial standardization is believed to be best administered by some voluntary association, yet a need for closer co-operation between Government and existing standards organizations seems to exist.

DURING the last 30 years our concept of standards has changed greatly. Initially we were concerned mainly with rather simple engineering standards—blood relation to the standards of the fundamental scientist. Gradually we have seen them evolve where necessary to incorporate elements primarily important to the operator and user or consumer. The circle of those around the council table has enlarged as has the field in which progress by standardization is essayed. Each major enlargement has almost invariably been accompanied by some element of conflict of opinion. The established standardizing group (or some of them) are, and for the most part wisely, hard to convert to radically new ideas projected from the outside and from peculiar angles.

In the early days engineers were forced into attempts at standardization in order that they might discuss intelligently matters of common interest; and to compare results. These matters were of little interest to others at the time. For the most part the work of their committees and associations was of scant concern to the community which was coming more and more to use and depend on the products of engineering craftsmanship. In this respect, more possibly than in any other, the changes wrought by three decades of evolution have been far-reaching not only on the operations of society but likewise on the methods and objectives of standardization itself.

The American Standards Association, which is the direct lineal descendant of the first engineering society standards committees, has come gradually into a position of great power and grave responsibility—greater and graver even than most of us appreciate, I suspect. Not only does its approval influence directly the things of industry with which it is concerned and the affairs of their users, but in many directions it becomes part of the base of statutory regulations, ordinances, or laws. It is from this angle that much of the Association's enhanced responsibility for careful, thoughtful, and meticulous functioning arises.

The formal ordinances or laws of the State are hardy "beasties," difficult to change and almost impossible of extermination. They spawn argument, conflict, and litigation at a prodigious rate and of a kind that gladdens the heart of those who like to fish in muddy water. Since much of the water is now of the Association's making, it behooves us to look well to its quality and filtration before turning it into the public distribution system.

Outside what I have observed of standardization in other fields of applied science, substantially all my ideas concerning its possibilities and limitations, concerning the objectives for which it is undertaken, and particularly concerning the basic rules which, it seems to me, should govern approach to the formulation of any standard, have been derived from the experience of nearly 35 years devoted to the orderly development of electrical communication. Throughout this entire period, standards and standardization have been looked upon as powerful tools for progress in the communication art. Occasionally, but not often in recent years, they have turned out to be serious obstacles to it.

Having determined many years ago to make the development of telephony and its collateral forms of electrical communication in the Bell System as far as possible an orderly process based on established principles of science and engineering, it was inevitable that standards and standardization should early come in for careful analysis.

Because of the peculiarly favorable conditions for unity of operation present in the structural setup of the Bell System—research, development, manufacturing, installation, and operation all under a common direction and with all parts of the organization concerned with a common objective—our experience might be considered in the nature of a trial installation of standardization under ideally controlled conditions.

While all of us have subscribed to the common objective of the best and most extensive service which science and art can provide at the lowest cost consistent with financial safety, I would not have you think we have been free from violent differences of opinions in the matter of standards to be adopted or altered. In so far as matters relating to standards were wholly of internal concern, the one thing we have been spared was the conflict of divergent views based on real or assumed differences of objective.

Since the only thing we sell to the public is service, we have in the main been free also from the ordinary manufacturer-customer conflict of requirements in our standardization of the material things required for giving that service. To a considerable extent it is immaterial to us which of two things we decided to standardize provided only that the one chosen when related to all the other factors which make up final over-all cost will give the best life service at the lowest cost. Thus as between two designs giving equally good operational results, we

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have no hesitancy in standardizing the one of higher initial cost if it is clear that by so doing we will save much more than the difference by reduced maintenance expense over its useful life.

Standards Are Short-Lived

My first study of standardization and the function and place of standards led me to certain conclusions, most of which have been strengthened by subsequent experience.

In the first place, it seemed clear that when the art had progressed far enough in any sector to make true standardization feasible, the establishment of standards and rigid adherence to them until they were superseded by better standards was the only certain way to ensure orderly and expeditious progress.

In the second place, it seemed clear that the standards set should take account of *all* the pertinent factors and should so far as possible omit *all* non-essential requirements; in a word, that they should make mandatory only those things clearly necessary in the attainment of a desired result and should leave maximum freedom for variation in all else.

In the third place, it appeared that standards should never be allowed to take on the habiliments of things sacrosanct but should be under continuous critical surveillance; that they should be discarded or modified promptly whenever it was clear that they had ceased to be tools of progress and become hindrances to it instead.

As a result of these and numerous other fundamental considerations which will occur to all of you, standards as we employ them in the Bell System are frequently short-lived affairs. We respect and value them for the help they give us while they live. We refuse to let them dominate our thinking and we discard them without a qualm when they become shackles. I think our attitude toward them might be expressed by saying that in our picture today's standards are today's statement of the most we know about the things we employ. Tomorrow's standards may or may not be the same. One thing we do when discarding an old friend is to be sure that the new one will serve us better and, so far as possible, have a definite bridge between the old and the new.

Another thing we learned early in our work was that a nice question was involved in determining just when to attempt standardization. If it was attempted too early in the development of a new thing or a new method we ran not only risk of wholesale use of something inferior to the best attainable, but to a considerable extent we shackled and strait-jacketed development. If standardization was too long deferred, development and use tended to run riot and produce a situation akin to one in which there were no standards or guide-posts to serve as definite points of departure.

On the whole I am inclined to think that the first, that is, a too early standardization, involves the greater hazard. It is a serious thing to stimulate the use of an inferior thing or method by designating it as a standard. It is a far more serious thing to shackle and delay development by so doing.

The establishment and promulgation of engineering or industrial standards always has a powerful influence on men's thinking and acting. There is universally a tendency to think and work *toward* a standard—seldom away from it, unless those concerned with the thing standardized appreciate fully that the standard is simply a transitory affair. Men will invariably spend more energy and thought in the direction of achieving the standard than they will on breaking new ground beyond it. They have a tendency to exercise their energy and inventiveness largely in devising cheaper ways than formerly of attaining standard results.

Where the established standard is distinctly above the average of the things to which it applies, this magnet-like tendency has its advantages because it stimulates those who are in the inferior position to seek a higher level, and, because they are in such case a majority, it acts to raise the general level even when it retards somewhat those who have been most progressive.

With premature standardization also all the forces involved are marshalled largely behind the status quo. Custom, established methods, money invested in tools or plant—all argue against change. It is so upsetting!! On the other hand, where proper standardization has been delayed beyond the time when it should have been done, the very turmoil and chaos of the resulting situation almost automatically impels conflicting interests to seek a common meeting ground. Further, from the welter of confused experience there is much material that can be salvaged in the making of a standard.

Standards Need Trial Period

Although I realize the difficulties inherent in the process, it has always seemed to me that the tool of "trial installation" could in many cases be a valuable addition to the machinery of standardization. Possibly in my ignorance of modern standard-making methods, I am advocating something which is already in effect. All that I have in mind is a field trial of the thing proposed on a sufficiently large scale and under sufficiently complete observational control to test thoroughly all the factors involved without committing everybody in advance to the new proposal. In a way the "tentative standard," or whatever you designate it, is along the lines I have in mind, although as I have observed its operation in some cases it seems to fall short of what I have in mind. It invites and depends too much on uncontrolled and unco-ordinated observation and so retards final decision and leaves that decision largely involved in a compromise of opinions.

In the Bell System where, as stated earlier, research and development, manufacturing, engineering, installation, and use are all looked upon merely as parts of a common problem, and where standardization is undertaken solely to insure the best that the current art affords and to facilitate improvement in the elements involved in rendering service, the controlled field trial has long been an established routine. No new thing of any importance is ever put into general use without it.

Primarily designed to bring to light defects or improve-

ments which have either been overlooked in the laboratory or which from their nature can only be determined in the field, the field trial serves almost automatically to determine the requirements of new standards which can and should be established for use, until they in turn are supplanted by still better ones. It is, in fact, use of industrial guinea pigs. While it does frequently involve experimentation on the ultimate consumer, it is only on a limited group of consumers, so that adverse reactions can never reach major proportions.

When it comes to how standards should be made and who should participate in their formulation, it has always seemed to me that machinery like that of the American Standards Association, or some body similar to it, is the only sensible kind to employ, except possibly in those fields involving matters of such vital importance to the general population that only political government has the power to cope with them.

Even here, however, it is hard to see how an organization such as the American Standards Association can fail to be of the utmost assistance. The technical and scientific world has become so complex, and controlling factors in almost every sector are found in such unexpected places, that only by having a forum where every one who has a right to be heard can be heard, are we assured of that final judgment which will command adherence and respect.

Furthermore, it is only from such a voluntary association that we can expect to have that degree of compromise without which no industrial standard, however perfect and desirable it may appear to its makers, can hope to succeed. I have observed that it is the exception rather than the rule when men are reasonably unanimous in acting like rational human beings. Ordinarily, we are a perverse lot who greatly dislike being told what we must or must not do even when we know that the prescription is clearly in our interest. If, however, we feel we have had our day in court we are usually ready to give the verdict a fair trial, including a peaceful appeal, if necessary, to the court if we are still dissatisfied, before we resort to arson and mayhem.

It is when we feel that our interests have been grossly outraged or our evidence slighted and passed over in the final decision that we put on our guerrilla togs and go out on a foray. All of this is just as true in the field of standardization as it is in any other area of human activity. Any standard which is made and promulgated in opposition to the fixed opinions, however acquired, of any considerable group involved in its operation, is foredoomed to hard sledding and almost certainly to failure. Such a group would be more than human if they did not seek to make it fail.

It was considerations such as these which long ago led me to feel that to be successful in the field of standardization the body responsible for a work which has become increasingly important to industry and commerce and to society generally, should have certain characteristics. It should be a voluntary association with the broadest possible constituency in the field of its interest; its operations should be democratic, with all that that implies of much essentially futile discussion and apparent procrastination; it should let facts, so far as they can be obtained, rather than opinions, determine the answer; finally, the Association itself should not be clothed with any police powers of enforcing its own findings—it should depend on the proven validity of its conclusions and the recognized standing of its members if it would insure general acceptance of its work.

Importance of Facts

Apropos of these two last points, I should like to remark that they but paraphrase observations made to me many years ago by two wise men, now dead, who were my friends—General J. J. Carty and Mr. Elihu Root. Early in my career as one of his assistants, General Carty impressed on me the importance of getting facts before forming opinions or drawing conclusions if one wished to obtain a valid and acceptable answer. It was his belief, and one he operated on consistently that the answer to almost any question was 90 per cent automatically self-evident if one took the trouble to assemble and scrutinize the known or ascertainable facts which bore on it. Anyone who was ever involved with him in consideration of some knotty problem will never forget the interminable hours, days, and even weeks or months which he devoted to fact-finding. It was soul and patience-trying and it led into most unexpected places and to most unexpected individuals but it got results that were rarely wrong.

Long ago Mr. Root pointed out to me the inherent fragility of action based primarily on legal authority and the almost irresistible power which inhered in the judgment of a body of men possessed of no power to enforce that judgment but who were recognized to be men of ability and character and who formed their opinions with studied deliberation.

Government Should Participate

My distrusts of Government as a maker of standards that affect commere and industry, that is, outside those sectors of public health or safety or national defense where Government alone can act, are more basic than fear of intrusion of political factors. They reside (1) in the belief that the agencies of Government, circumscribed as they are of necessity by the restraints of Government, are not in the best position to obtain and appraise all the facts; and (2) that being agencies of Government anything they emit tends to appear more important than it really is and more difficult to abandon or modify.

In other words, standards made by Government are, it seems to me, more likely to become instruments of restraint to progress than are those emanating from a mobile body like the American Standards Association. When to this is added the almost inevitable tendency that develops in men clothed with apparent authority to exercise it punitively, it seems to me that the case for the voluntary association in the field of standardization is substantially iron-clad.

Nothing of what I have just said should be construed as a belief on my part that Government should be excluded from participating in the making of standards—quite the contrary. Government should participate largely but, I think, on the same voluntary basis as the other members of the Association. Added to its general concern in establishing standards wherever these are clearly in the public interest, Government in times of peace is itself a large consumer and so entitled to be heard. In times of war it is the largest consumer. Anything in the direction of wise standard making in times of peace which will facilitate the functioning of Government and industry in time of war is obviously in the common interest.

I know that all the foregoing is "old stuff" to the Association and I am not saying it with any thought that it need be said here where all agencies—governmental and nongovernmental—meet together. What I really had in mind in saying what I have is that possibly my opinion based on long experience may add a pebble to the dyke which periodically has to be raised against a demand that Uncle Sam take on part or all of this standardizing job because he can do it so much better or so much faster. It is usually a plausible tale that is told and it has only one demerit—it is not true.

In concluding I do not know that I can do better than attempt in brief summary to restate my own picture of what proper industrial standards should be, how and by whom they can best be formulated, and some of the things which appear to me we should guard against in their use.

"Industrial" and "Absolute" Standards Differ

Before doing this I should like, however, to emphasize two things which, while interrelated, are frequently badly confused particularly by the nontechnical public. First, industrial standards are essentially different from the so-called "absolute" standards of science—such, for example, as the unit of time. The "absolute" standards if accurately determined and readily reproducible are "absolute" in a very real sense—they are ordinarily not subject to change with advancing knowledge. They are the scales by which we measure it.

Industrial standards on the other hand are akin to the hypotheses of the scientist. They define our present state of knowledge and they live only so long as they continue to define adequately. As soon as they fail so to define, they are for all practical purposes as dead as the ancient dodo or the great auk and like them are of interest only in a museum.

To the nontechnical this difference is not generally understood and from the misunderstanding arises much difficulty. To them, "standard" has come to denote something fixed, final, and generally desirable. They instinctively resent anything which seems to cast doubt on its paternity and they impute base motives to all who advocate change despite the fact that changing industrial standards are the very hallmark of industrial progress.

Now for my summary picture.

Standards Are Tools for Progress

To me a proper engineering or industrial standard is a temporary statement which includes all that is really essential of proven current knowledge to define the thing standardized. It is a specification which can be met in current commercial practice and a tool by which the art can progress. It carefully excludes everything which is nonessential in order to insure maximum latitude alike to the developer and user. In a word, it is a common meeting place for purchaser and seller with no signs of *caveat emptor* about. It is continually under scrutiny by all who have occasion to use it and is subject to ruthless modification or abandonment as soon as it has clearly ceased to function as intended.

It is created by a voluntary association of all groups who have a definite interest in its existence and by representatives of them chosen because of established reputation for competence and ability to weigh evidence, honestly and impartially. The standardizing body itself should be without legal power to enforce its conclusions but like the Supreme Court should depend on the recognized merit of its findings. Where reasonable doubt exists as to the necessity for standards, the Association should err on the side of too few rather than too many.

Where it is known or believed that the standard sought to be established is likely to become adopted into ordinances or laws and so subject to administration by men, who have legal authority of enforcement, the obligation on the Association to be meticulous in its final decision is greatly enhanced. Merely to clothe a standard with the habiliments of ordinance or law is to lessen materially our ability to change promptly in the face of changing conditions. With increasing prestige of the American Standards Association there will inevitably be increasing tendency for our gentlemen and lady "fixits" to enact laws based on its authority. Like "De Lawd" in "Green Pastures," we are great on passing miracles in the form of laws. The only thing that saves us from our sins in this respect is that we don't take the matter too seriously—not even seriously enough to want to stop the practice.

What Is Tensor Analysis?

Part II—Differential Properties

By BANESH HOFFMANN

Having procured in a previous part of this article* a good specimen in the "hunt" for the tensor, the author proceeds here to catalog most of the characteristics of the catch. Among other subjects, discussions of tensor fields, tensor notation, and rules for transformation are included in this part. The finale, part III, will give the reader an inkling of the importance of tensor applications in physics and engineering.

IN PART I we saw how simple are the essential algebraic ideas of tensor calculus. We shall now discuss the concepts upon which the differential properties of tensors are based. There are but two new concepts to be considered—tensor fields and covariant derivatives—and once the ideas of part I have been grasped these will present no real difficulties.

Fields, of course, are of all conceivable varieties. For instance, there are just ordinary, plain fields, and a'so playing fields; wheat fields, magnetic fields, and outfields; fields of endeavor and fields of vision; field days, field marshals, martial fields, and even Marshall Fields! And now there are to be *tensor* fields.

Tensor fields bear a more or less close relation to the various other types of field. The reader will certainly not deny, for example, that they constitute a most strenuous field of endeavor. In this article, however, we shall stress mainly their relation to such things as magnetic fields; and, curiously enough, to martial fields, too.

We are all familiar with those picturesque experiments in elementary physics in which iron filings are made to reveal the field of a magnet spreading its influence throughout space. The filings line up in long streaks from one pole of the magnet to the other, following the direction of the magnetic intensity at every point. Even a superficial glance at the pattern of filings shows that at different places the magnetic intensity has different directions. A closer examination discloses that the magnitude of the intensity also varies from place to place. At each point of space the magnetic intensity is a genuine vector, satisfying all the requirements laid down for vectors in part I. To describe the whole magnetic field we must therefore use a separate vector for each point of space. We need, in fact, a whole army of vectors—and here is where the relationship with martial fields first comes in. Such an army of vectors, a separate vector for each point of space, is what is meant by a vector field in space. And, as we would expect, a tensor field is merely a similar conglomeration of tensors.

A tensor field, then, actually consists of an infinite number of separate tensors. It would seem at first sight that such an army of tensors would be quite unmanageable in practice. Remember, though, that it is no rabble, but a well-drilled army. On a martial field a good army sergeant, endowed with powerful lungs, and an equally "powerful" vocabulary, can inspire such terror that he can drill a whole battalion as easily as he can drill a single soldier. So, too, the mathematician, on his field of paper, can actually handle the infinite army of tensors constituting a tensor field with as little effort as he would have to put forth on a single tensor.

It usually happens in tensor analysis that the mathematical tricks used in overcoming the various difficulties which arise are already quite familiar from other branches of mathematics. The trick which makes possible the present miracle of organization and control is no exception. Consider, for example, the manner in which we habitually handle the gravitational potential near the earth's surface. If a mass m is at a small height z above the earth's surface, we say that its potential is

$$V = mgz \qquad (2.1)$$

In saying this, however, are we not dealing, not with a single potential, but with an infinite number of potentials all at once, a separate one for each point (x, y, z) of space? The potential at any particular point is a scalar, and the potential function V is thus nothing but a scalar field; which, of course, is the simplest type of tensor field. Yet we have so little trouble with it we hardly ever stop to realize that the mathematical device which lets us deal so glibly, yet so authoritatively, with an infinite number of scalars all at once is the use of a *function of position* to describe the whole scalar field.

For a general tensor field we use exactly the same trick, making each separate component a function of position and thus writing the whole tensor field in the compact form

$$T^{ab\ldots}_{cd\ldots}(x^e) \qquad (2.2)$$

Of course, the notation 2.2 is not very enlightening as yet. So let us away to our happy hunting ground of part I and see what we can find in its depths. Perhaps, to be in the present fashion, we should refer to it now as our happy hunting field.

*Written especially for ELECTRICAL ENGINEERING, this is the second of three parts of an article presented because of the widespread interest in the subject among Institute members. Part I appeared in the January 1938 issue, pages 9–9; part III will appear in a subsequent issue. ALL RIGHTS RESERVED BY THE AUTHOR.

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In part I we pulled on the co-ordinate axes of equation 1.1 with such determination that in the end even the tensor g_{ab} was forced to show itself. It showed itself though, only as a single tensor. And the truth is that it is really a whole tensor field. To make it "come clean" we must go the limit with our third degree. However much we distorted the co-ordinate lines in part I we always stopped short of actually bending them. But now, in our brutality, we must forget such humanitarian scruples.

There is no advantage in bending the co-ordinate lines into fantastic shapes, when we already have a very familiar curvilinear co-ordinate system in polar co-ordinates, as shown in figure 4.

In polar co-ordinates the distance between the two neighboring points (r, θ) and $(r + dr, \theta + d\theta)$ is given by the well-known formula:

$$(ds)^2 = (dr)^2 + r^2(d\theta)^2 \qquad (2.3)$$

How this formula can be obtained from the tensor calculus must wait until we have discussed the laws of transformation of tensor fields. Meanwhile, there is no reason why we should not rewrite it in tensor notation. It then becomes our old friend

$$(ds)^2 = g_{ab}dx^a dx^b \qquad (2.4) = (1.37)$$

where

$$dx^a = (dx^1, dx^2) = (dr, d\theta) \qquad (2.5)$$

and

$$g_{ab} = \begin{vmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{vmatrix} = \begin{vmatrix} 1 & 0 \\ 0 & (x^1)^2 \end{vmatrix} = \begin{vmatrix} 1 & 0 \\ 0 & r^2 \end{vmatrix} \qquad (2.6)$$

The important thing to notice here is that g_{22} is no longer a constant. In part I all of the components of g_{ab} were constants. Here one is not. The value of g_{22} in polar co-ordinates is different at different places. At $(1, \pi/4)$ for instance, it is unity, but at $(3, \pi/4)$ it is nine. We really have different tensors g_{ab} at different places. In fact, in g_{ab} we have been harboring a whole tensor field unawares.

In polar co-ordinates the g_{22} at any place depends on the value of r for that place. It is merely by chance that it does not also depend on the value of θ; and that the other components g_{11}, g_{12}, and g_{21}, still happen to be constants. You would not want me to bend the poor co-ordinate system still more just to show you that g_{22} can be made to depend on both co-ordinates, and that g_{11}, g_{12}, and g_{21} can be shaken out of their constancy and made to vary from point to point also. To do that would be downright sadism. Let us simply take it on trust. In part I, because the components of g_{ab} were all constants, and thus did not alter as we went from place to place, we overlooked the fact that we really had separate, even though numerically equal, tensors g_{ab} for every point of the plane. Simply because these tensors all looked alike we lumped them together in our minds as a single tensor. This was as bad as if we had thought that an army consists of a single soldier because all the soldiers wear he same uniform and happen to be standing in the same attitude, facing in the same direction. Bending the co-ordinate lines is like sending the army to the wars, for then the uniforms become covered with mud and each soldier is clearly distinguishable as an individual by his personal heroism or cowardice.

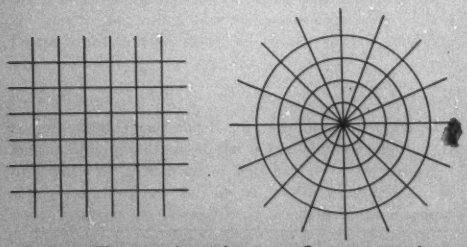

Figure 4. The co-ordinate lines in a Cartesian co-ordinate system (left) are straight, therefore unable to reveal that g_{ab} is a tensor field, and the use of a curved co-ordinate system, such as polar co-ordinates (right) is necessary

Tensor Notation

So much for the general idea of a tensor field. What of the notation 2.2?

Well, first of all, how could we denote that the g_{22} of equation 2.6 is a function of r? The standard notation for a function f of x is $f(x)$. We therefore write for this function $g_{22}(r)$, or, since r is x^1, $g_{22}(x^1)$. But suppose we had so tortured the co-ordinate system that g_{22} depended on x^3 as well as on x^1. Then, following standard practice, we should have to write $g_{22}(x^1, x^3)$. And since (x^1, x^3) is written in the compact form x^a, we can write this as $g_{22}(x^a)$. Finally, suppose we had gone over to a co-ordinate system so terribly warped that not only g_{22} but all the other components of g_{ab} also became dependent on x^1 and x^3. We should then have to write the components of g_{ab} as $g_{11}(x^a)$, $g_{12}(x^a)$, $g_{21}(x^a)$, and $g_{22}(x^a)$. And if we now collect all these components in a single filing envelope in accordance with the basic tensor notation, we must give them the label

$$g_{ab}(x^a) \qquad (2.8)$$

And that is the sort of thing that is meant by the notation 2.2.

It is now time for an apparent digression upon the waywardness of mathematicians. If the mathematician is able to exhibit a graph of y against x he argues that there is some relationship between y and x, and accordingly writes $y = f(x)$. Suppose, though, that the graph is something like figure 5. Can he really say $y = f(x)$ for this graph? The "relationship between y and x" has here been reduced to $y = 2$. Where is the x? Any ordinary person would admit at once it isn't there. But that is far too naive for the mathematician. He says the x is really there, only you don't notice it. And if you press him, he will suggest that it is multiplied by zero. And if you still don't believe him, he will either walk away with an air of Hamletical despair, or else he will "prove" to you that the x is thereby altering the co-ordinate system (as perhaps you are already bitterly

aware!). If he simply tilts the co-ordinate system, the line will slope relative to the x axis, and its equation will then take the form

$$y = mx + b$$

And behold, there is your x!

It is useless to argue with him; useless to tell him he just put it there. The plain truth, of course, is that there really was no x in the first place. But the mathematician was also right when he said that this was because the x was multiplied by zero. Where the quarrel really starts is over the philosophical question whether no x is no x or some x. And who is to decide?

The mathematician has the trump card. He can always say it is a question involving x's and y's; therefore, a mathematical question; therefore one which only a mathematician may competently discuss; Q. E. D. And there is no convincing answer to that. So the mathematician goes blithely on using $f(x)$ to denote not only genuine functions of x, but also mere constants, and even zero. (He will object to that last distinction, of course, saying that zero is simply another constant.)

And now, since tensor analysis is a mathematical subject, we must go along with the mathematician and agree that even in Cartesian co-ordinates the components of g_{ab}, though constants, are functions of the co-ordinates. This way of talking has its advantages too. For now we need make no exceptions for special co-ordinate systems. The notation 2.8 is now valid under all conditions.

All of which will hardly prepare us for the next shattering blow. Incredible as it may seem, the mathematician is so lazy he usually ignores the notation 2.8 and reverts to the notation g_{ab} of part I even when he is dealing with fields! Books on vector and tensor analysis are often very confusing because of this, and the only consolation I have to offer you is that very soon you yourself will be indulging in this lazy habit along with the best mathematicians—a sure sign of progress.

Rules of Transformation for Tensor Fields

We now come to a very important point. Is there a law of transformation which will do for a whole tensor field what transformation 1.14 did for a single tensor in part I? Let us once more liken our tensor field to an army. There are two essentially different types of command that a drill sergeant can shout at his company. If he shouts "forward march," the soldiers all do exactly the same thing. But if he shouts "open ranks march," the effect is selective; half of the soldiers go through a maneuver while the rest simply stand still. A more extreme example of this second type is the command to a gun crew to "prepare for action." Here each man does a different thing.

In part I we were concerned solely with transformations analogous to commands of the first type, producing the same effect on each individual tensor of the field. That is why we mistook the whole tensor field for a single tensor. What we are looking for now is a law of transformation which will correspond to "open ranks" and "prepare for action," treating each tensor of the field as an individual if necessary.

How could we handle so chaotic a situation mathematically? The situation holds no real terrors. We know by now exactly how to meet it. We need a few more functions of position, that is all. The ordinary law of transformation for a single tensor was given in equation 1.14 in part I. For simplicity, let us consider a tensor with only one suffix of each type. The law of transformation for this sort of tensor is, in accordance with the transformation law 1.14,

$$\overline{T}^p_q = T^a_b C^p_a c^b_q \tag{2.11}$$

This, remember, is for a single tensor. When we have a tensor field we represent it by writing the components as functions of position, as $T^a_b(x^e)$. This tells us the value of each component of each tensor of the field. We now do the same sort of thing with the transformation law. There being a special "made to measure" transformation for each tensor of the field, and thus for each point, we represent the whole lot all at once by means of C's and c's which are functions of position. In this way we can treat a plague of transformations attacking an army of tensors as simply as we can treat the transformation of a single tensor. We write for this epidemic the all-inclusive formula:

$$\overline{T}^p_q(\overline{x}^r) = T^a_b(x^e) C^p_a(x^e) c^b_q(x^e) \tag{2.12}$$

where everything in sight is a function of position, and the summation convention does not apply to the repeated suffix e since it is not a tensor suffix. This hard-working formula actually does the work of transformation 2.11 in an infinite number of places simultaneously. Each tensor of the field finds itself undergoing a transformation of the type considered in part I and represented by transformation 2.11—a rotation or stretching of the local co-ordinate system, or a combination of both.

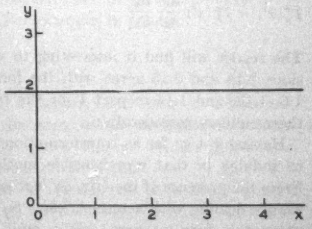

Figure 5. That a relationship between y and x exists for the graph y = 2 is clear only to the mathematician, who resorts to trickery to prove the relationship

Now formula 2.12 will take care of the most chaotic conditions. But in many cases the various local transformations, far from being haphazard, are related to each other in quite a regular manner. This is especially true when all these local rotations and stretchings are caused by a transformation of the whole co-ordinate system of the whole field. The change from Cartesians to polars is an example. A transformation of the whole co-ordinate system of the whole field is called a *holonomic transforma-*

tion. All others, in which the local rotations and stretchings are not related in this comparatively simple way, are called *nonholonomic transformations.* The distinction is an extremely important one. In fact some of the most significant tensor fields in mathematics and physics are tensor fields only if we limit ourselves to holonomic transformations.

When we are dealing with holonomic transformations we can make a significant alteration in formula 2.12. The most general holonomic transformation of the co-ordinates of the whole field is of the type:

The new co-ordinate $\bar{x}^1$ is some given function of the two old co-ordinates (x^1, x^2);

The new co-ordinate $\bar{x}^2$ is some other given function of the two old co-ordinates (x^1, x^2).

The standard notation for compressing this into one compact formula is:

$$\bar{x}^\rho = \bar{x}^\rho(x^\beta) \tag{2.13}$$

and a little consideration will show that it is the natural one.

The question now arises: how much rotating and stretching of the local co-ordinates at each point is implied by such a transformation? The local transformations are all of the type of transformation 2.11, and by making a Taylor expansion of formula 2.13 it can be shown that the local effect may be represented by C's and c's which at each point have the values given by:

$$C^\rho_\alpha = \frac{\partial \bar{x}^\rho}{\partial x^\alpha} \quad ; \quad c^\beta_\gamma = \frac{\partial x^\beta}{\partial \bar{x}^\gamma} \tag{2.14}$$

Thus when we are dealing with a holonomic transformation—of which equation 2.12 is the general type—we may replace formula 2.12 by the more specialized law of transformation

$$\overline{T}^\rho_\gamma(\bar{x}^\tau) = T^\alpha_\beta(x^\sigma)\frac{\partial \bar{x}^\rho}{\partial x^\alpha}\frac{\partial x^\beta}{\partial \bar{x}^\gamma} \tag{2.15}$$

The reader will find it interesting to verify that expressions 2.14 and 2.15 agree with the formulas of the type 1.6, 1.13, and 1.14 in part I for the transformations 1.5 there under consideration.

Having got as far as transformation 2.15, we can afford to indulge in that reprehensible mathematical laziness. From the presence of the $(\partial x/\partial x)$'s it is quite evident that we are dealing with a tensor *field.* So unless we wish to stress this fact we may safely omit the $(\bar{x}^\tau)$ and (x^σ) and write transformation 2.15 in the lazy form

$$\overline{T}^\rho_\gamma = T^\alpha_\beta \frac{\partial \bar{x}^\rho}{\partial x^\alpha}\frac{\partial x^\beta}{\partial \bar{x}^\gamma} \tag{2.16}$$

This is the way it usually appears in the textbooks, and unless the reader is fully aware that it is not really complete he is likely to get an entirely erroneous impression of the true meaning of the equation.

Suppose we happen to be given the transformation, not in the form of equation 2.13, which would guarantee it to be holonomic, but in terms of the C's and c's. How can we tell if it is holonomic? The test is simple. Take C^ρ_α for instance. If expression 2.14 is to hold, we must have

$$\frac{\partial C^\rho_\alpha}{\partial x^\beta} = \frac{\partial^2 \bar{x}^\rho}{\partial x^\beta \partial x^\alpha} = \frac{\partial^2 \bar{x}^\rho}{\partial x^\alpha \partial x^\beta} = \frac{\partial C^\rho_\beta}{\partial x^\alpha}$$

An analogous result holds for c^β_γ. So, to test whether a transformation $C^\rho_\alpha(x^\sigma)$, $c^\beta_\gamma(\bar{x}^\tau)$ is holonomic see whether

$$\frac{\partial C^\rho_\alpha(x^\sigma)}{\partial x^\beta} = \frac{\partial C^\rho_\beta(x^\sigma)}{\partial x^\alpha} \quad ; \quad \frac{\partial c^\beta_\rho(\bar{x}^\tau)}{\partial \bar{x}^\rho} = \frac{\partial c^\beta_\rho(\bar{x}^\tau)}{\partial \bar{x}^\tau} \tag{2.17}$$

If so, the transformation is holonomic; if not, the transformation is nonholonomic.

From now on we shall deal only with holonomic transformations.

To illustrate this abstract discussion, let us consider the change from Cartesians to polars already touched upon in this article. Equation 2.13 here means the well-known relations.

$$x = r\cos\theta, \quad y = r\sin\theta. \tag{2.18}$$

To put these into more tensorial notation we write

$$(x^1, x^2) \text{ for } (x, y); \quad (\bar{x}^1, \bar{x}^2) \text{ for } (r, \theta) \tag{2.19}$$

Then definition 2.18 is

$$x^1 = \bar{x}^1\cos(\bar{x}^2); \quad x^2 = \bar{x}^1\sin(\bar{x}^2) \tag{2.20}$$

Notice that in this form definition 2.20 is not really like formula 2.13 but like

$$x^\alpha = x^\alpha(\bar{x}^\rho) \tag{2.21}$$

It makes no difference which form, 2.13 or 2.21, we talk about; in fact we invariably talk about both at once, since if x^α are functions of $\bar{x}^\rho$, then $\bar{x}^\rho$ are functions of x^α.

Let us apply this transformation to the metrical tensor field $g_{\alpha\beta}$ according to the rules just developed and see how it leads to the result already given in equation 2.6. For a doubly covariant tensor field like $g_{\alpha\beta}$ the law of transformation corresponding to equation 2.16 is, of course,

$$\bar{g}_{\rho\tau} = g_{\alpha\beta}\frac{\partial x^\alpha}{\partial \bar{x}^\rho}\frac{\partial x^\beta}{\partial \bar{x}^\tau} \tag{2.22}$$

Here $g_{\alpha\beta}$ are the components in Cartesians, and $\bar{g}_{\rho\tau}$ the corresponding components in polars. From definition 2.20 we have, by elementary differentiation:

$$\frac{\partial x^\alpha}{\partial \bar{x}^\rho} = \begin{vmatrix} \frac{\partial x^1}{\partial \bar{x}^1} & \frac{\partial x^1}{\partial \bar{x}^2} \\ \frac{\partial x^2}{\partial \bar{x}^1} & \frac{\partial x^2}{\partial \bar{x}^2} \end{vmatrix} = \begin{vmatrix} \cos(\bar{x}^2) & -\bar{x}^1\sin(\bar{x}^2) \\ \sin(\bar{x}^2) & \bar{x}^1\cos(\bar{x}^2) \end{vmatrix} \tag{2.23}$$

We know, of course, that

$$g_{\alpha\beta} = \begin{vmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{vmatrix} = \begin{vmatrix} 1 & 0 \\ 0 & 1 \end{vmatrix} \tag{2.24}$$

and what we want to show is that we do actually get the correct polar form of the metrical tensor, namely

$$\bar{g}_{\rho\tau} = \begin{vmatrix} \bar{g}_{11} & \bar{g}_{12} \\ \bar{g}_{21} & \bar{g}_{22} \end{vmatrix} = \begin{vmatrix} 1 & 0 \\ 0 & r^2 \end{vmatrix} \tag{2.25}$$

Applying transformation 2.22 and using equations 2.23 and 2.24, we have

$$\bar{g}_{11} = g_{11}\frac{\partial x^1}{\partial \bar{x}^1}\frac{\partial x^1}{\partial \bar{x}^1} + g_{12}\frac{\partial x^1}{\partial \bar{x}^1}\frac{\partial x^2}{\partial \bar{x}^1} + g_{21}\frac{\partial x^2}{\partial \bar{x}^1}\frac{\partial x^1}{\partial \bar{x}^1} + g_{22}\frac{\partial x^2}{\partial \bar{x}^1}\frac{\partial x^2}{\partial \bar{x}^1}$$
$$= \cos^2(\bar{x}^2) + 0 + 0 + \sin^2(\bar{x}^2) = 1$$

$$\bar{g}_{12} = g_{11}\frac{\partial x^1}{\partial \bar{x}^1}\frac{\partial x^1}{\partial \bar{x}^2} + g_{12}\frac{\partial x^1}{\partial \bar{x}^1}\frac{\partial x^2}{\partial \bar{x}^2} + g_{21}\frac{\partial x^2}{\partial \bar{x}^1}\frac{\partial x^1}{\partial \bar{x}^2} + g_{22}\frac{\partial x^2}{\partial \bar{x}^1}\frac{\partial x^2}{\partial \bar{x}^2}$$
$$= -\bar{x}^1\cos(\bar{x}^2)\sin(\bar{x}^2) + \bar{x}^1\sin(\bar{x}^2)\cos(\bar{x}^2) = 0$$

$$\bar{g}_{21} = \ldots = 0$$

and

$$\bar{g}_{22} = g_{11}\frac{\partial x^1}{\partial \bar{x}^2}\frac{\partial x^1}{\partial \bar{x}^2} + g_{12}\frac{\partial x^1}{\partial \bar{x}^2}\frac{\partial x^2}{\partial \bar{x}^2} + g_{21}\frac{\partial x^2}{\partial \bar{x}^2}\frac{\partial x^1}{\partial \bar{x}^2} + g_{22}\frac{\partial x^2}{\partial \bar{x}^2}\frac{\partial x^2}{\partial \bar{x}^2} =$$
$$= (\bar{x}^1)^2\sin^2(\bar{x}^2) + (\bar{x}^1)^2\cos^2(\bar{x}^2) = (\bar{x}^1)^2 = r^2$$

all of which agrees with equation 2.25.

Covariant Derivatives

There remains one last mystery for our consideration; the covariant derivative. It is well-nigh indispensable in advanced work involving tensors. Unfortunately, though, it is one of the most elusive concepts in all tensor analysis. With such a concept as our quarry there is only one sensible thing left for us to do; go back at once to our happy hunting field, equation 1.1.

In equation 1.1 the metrical tensor is so uniform it goes far beyond giving the impression of being only one tensor instead of a whole field; it actually seems not to be there at all. To make it show up, even in the guise of a single tensor, we had to go over to co-ordinate systems less regular and symmetric than Cartesians; and to bring out the tensor field in all its glory would require the use of quite grotesque co-ordinate systems such as we have not dared display here.

Let us first ask what we mean by a uniform magnetic field. A magnetic field is uniform if the intensity is the same at all places; that is, if the various vectors representing the field at its various points are all alike. But this does not mean that the x^1 components of all these vectors will turn out to be all equal, and the x^2 components likewise. That will only be true if we use a specially simple co-ordinate system, such as the Cartesian. This is well illustrated by the behavior of the metrical tensor field g_{ab}. In Cartesian co-ordinates the components g_{11} of the individual tensors of the field are all unity, the g_{12} and g_{21} zero, and the g_{22} unity again. But as soon as we go over to polar co-ordinates we find that, for example, g_{22} at $(1, \pi/4)$ and g_{22} at $(2, \pi/4)$ are, respectively, one and four. The tensor field no longer looks uniform.

What has happened? Has the tensor field actually become nonuniform? Let us go back to to the uniform magnetic field; it is easier to think about a familiar concept. If we go from Cartesians to polars, the vector field representing this uniform magnetic field will no longer look uniform in terms of its new components. But in changing the co-ordinate system we have done no fuse blowing, rheostat turning, or dynamiting. The cumbersome apparatus producing the uniform field is just the same as it was before. The magnetic field is just as uniform as before. All that has happened is that we have decided to use a new mathematical procedure for talking about it. This gives us the answer to our previous question. Since the metrical tensor field g_{ab} is uniform in the standard uniform co-ordinate system known as Cartesian, it is uniform, and that is that. Any apparent lack of uniformity which may enter when we change to a different co-ordinate system is our own fault for changing to that co-ordinate system. The field remains as uniform as ever. If it did not the whole idea of a tensor would be short-circuited. For a tensor must be essentially independent of the particular co-ordinate system used.

If I choose to look at myself in a distorting mirror, I can well afford to laugh since I know I don't really look quite as funny as I seem to. In just the same way the uniform tensor field can afford to laugh at its peculiar reflection in distorting co-ordinate systems; it knows very well it is still uniform.

That the tensor field g_{ab} is uniform seems an innocent enough statement. But note that it is an objective one; changing the co-ordinates has nothing to do with it. The chances are, therefore, that the mathematical way of expressing it will be in terms of a tensor equation. In Cartesians, of course, we can express the uniformity of the metrical tensor field by writing

$$\frac{\partial g_{ab}}{\partial x^c} = 0 \qquad (2.27)$$

This is not valid, however, once we go over to curved co-ordinate systems. For example, in polars

$$\frac{\partial g_{22}}{\partial x^1} = \frac{\partial (r^2)}{\partial r} = 2r \neq 0$$

If $(\partial g_{ab}/\partial x^c)$ were a tensor, and zero in Cartesians, it would have to be zero in all co-ordinate systems. It is thus evidently not a tensor, despite its suffixes. Three suffixes do not a tensor make!

Our problem can be considered in a more general manner. Suppose we have a tensor field $T^{ab\ldots}_{cd\ldots}(x^e)$, uniform or nonuniform. In curved co-ordinate systems the components are likely not to be constants. How can we distinguish between the lack of constancy of the components caused by an essential lack of uniformity of the tensor field, and a bafflingly similar type of inconstancy due solely to the use of a curved co-ordinate system? The problem seems formidable. It is just as if we were looking at a man's reflections in several distorting mirrors and trying to tell, without looking at him directly, whether or not he had curvature of the spine. Fortunately we have formulated our problem carefully; it is, therefore, practically solved.

What we need is a "curvilinearity meter" which will

measure the amount of inconstancy due solely to the curvature of the co-ordinate lines. If we can measure this amount we can subtract it from the *total* inconstancy in any given co-ordinate system, this total inconstancy being, of course, measured by the nontensor 2.28, and shall then have left the amount of inconstancy for which the tensor field itself must take the blame. This last is the precise measure of the absolute, intrinsic lack of uniformity of the tensor field, the effect of the co-ordinate system having been completely filtered out. It is thus independent of the particular co-ordinate system used and, as we should therefore expect, turns out to be a true tensor field. This tensor field is called the *covariant derivative* of the original tensor field.

The only problem remaining is how to measure the effect of the curvilinearity of the co-ordinates. Well, why not use the metrical tensor field g_{ab}? We have already seen how extremely sensitive it is to the slightest disturbance of the co-ordinate system. It should thus be the basis for an ideal curvilinearity detector.*

In practice it turns out that the most convenient detector is not the simple nontensor field $(\partial g_{ab}/\partial x^c)$ but the rather more complicated *Christoffel symbols of the second kind* denoted by $\left\{ {a \atop bc} \right\}$. These quantities are defined in all books on tensor analysis and their derivation explained in various ways. They are given by

$$\left\{ {a \atop bc} \right\} = g^{ae} \left(\frac{\partial g_{ce}}{\partial x^b} + \frac{\partial g_{be}}{\partial x^c} - \frac{\partial g_{bc}}{\partial x^e} \right) \tag{2.29}$$

where g^{ae} is related to g_{ab} by

$$g^{ae} g_{eb} = \delta^a_b \tag{2.30}$$

The Christoffel symbols are not tensors. They measure directly the effect of the curvilinearity of the co-ordinate system upon any type of tensor at so much per suffix. For example, for a vector field of the type V_a, the amount of inconstancy caused by the co-ordinate system alone turns out to be $V_e \left\{ {e \atop ab} \right\}$, summed over the repeated suffix e. Since the total inconstancy is $(\partial V_a/\partial x^b)$, the portion of this total inconstancy due solely to the nonuniformity of the vector field itself is measured by the covariant derivative of V_a, which is denoted by $V_{a,b}$ and defined by

$$V_{a,b} = \frac{\partial V_a}{\partial x^b} - V_e \left\{ {e \atop ab} \right\} \tag{2.31}$$

This $V_{a,b}$ is a true tensor field.

For an upper suffix the effect of curvilinearity of the co-ordinates is slightly different. Evidently it could not be the same because the summation over the previous repeated suffix would no longer be possible. For a vector field W^a, the effect of the co-ordinates turns out to be $-W^e \left\{ {a \atop eb} \right\}$. So the covariant derivative of W^a is defined by

$$W^a_{,b} = \frac{\partial W^a}{\partial x^b} + W^e \left\{ {a \atop eb} \right\} \tag{2.32}$$

*It is not essential to use g_{ab} for this purpose. Kron uses the impedance tensor Z_{ab}. In geometry the use of g_{ab} has many advantages, into which it is not necessary to enter here. Whatever the second rank tensor used for forming covariant derivatives, it should, in general, be this same tensor which is used for the operations of raising and lowering suffixes described in all the textbooks. Kron's use of Z_{ab} is consistent with this.

Each separate suffix of a tensor field produces its own effect on the covariant derivative. Thus for the metrical field g_{ab} the covariant derivative is given by

$$g_{ab,c} = \frac{\partial g_{ab}}{\partial x^c} - g_{eb} \left\{ {e \atop ac} \right\} - g_{ae} \left\{ {e \atop bc} \right\} \tag{2.33}$$

It turns out, from equations 2.29 and 2.30, that the right-hand side of equation 2.33 is identically zero. This was inevitable, since g_{ab} is a uniform tensor field according to our definition of uniformity.

There is also a contravariant derivative, but it is a trivial extension of the covariant derivative and practically never used.

When we go over to Cartesian co-ordinates, what happens to the covariant derivative of a tensor field? The covariant derivative of a tensor field of the general type $T^{ab\cdots}_{cd\cdots}$ has the following structure. First comes the ordinary spatial derivative $(\partial T^{ab\cdots}_{cd\cdots}/\partial x^e)$. Then comes a long string of $T\{\}$'s, one for each upper suffix. And finally another long string of $T\{\}$'s, one for each lower suffix. In Cartesians the components of g_{ab} are constants. Therefore the quantities $(\partial g_{ab}/\partial x^c)$ are all zero. So, by equation 2.29, all the $\left\{ {a \atop bc} \right\}$ become zero. Hence in Cartesians the covariant derivative of $T^{ab\cdots}_{cd\cdots}$ reduces simply to its ordinary spatial derivative $(\partial T^{ab\cdots}_{cd\cdots}/\partial x^e)$. In Cartesians, therefore, it measures what we want it to; the true rate of change of $T^{ab\cdots}_{cd\cdots}$ as we move from place to place. Since, however, it is a genuine tensor field, it does in every co-ordinate system what the nontensor $(\partial T^{ab\cdots}_{cd\cdots}/\partial x^e)$ is able to do only in Cartesians and a few other simple co-ordinate systems. In tensor analysis, then, whenever one is tempted to use the ordinary spatial derivative of a tensor, it usually happens that one ought instead to use its covariant derivative. The covariant derivative *is*, in fact, the ordinary derivative, the so-called ordinary derivative being actually a most extraordinary nontensor having no objective significance!

One final remark. The covariant derivative of any tensor field has one lower suffix more than the original tensor field. This shows us how to remember which are the covariant and which the contravariant suffixes.

Westinghouse Photo

Stray-Current Electrolysis—Some Fundamentals

By C. M. LONGFIELD
MEMBER AIEE

Corrosion of metal buried in the earth, such as oil, gas, and water pipe lines and cable sheaths, by stray currents from grounded-return circuits such as railways is a subject of growing interest and importance. Conflicting theories prevail, but this article aims to present unbiased results from a fundamental investigation.

NOTWITHSTANDING the vast amount of literature that has been poured out on the subject of electrolysis in the past decade, no one can say that the matter has been put upon a satisfactory engineering basis. The fact that stray-current corrosion is so often confused with its half brother, chemical corrosion, makes it more difficult to sift out cause and effect. The situation is often complicated by the fact that one or more of the utilities involved in a given area observe an official reticence which is engendered, either by a misunderstanding of the fundamentals of the problem, or by the attitude of other affected parties. In the author's opinion, there is nothing occult in stray-current electrolysis, nor is the occurrence of electrolysis necessarily a sign of negligence. It is not a legal or constitutional matter so much as a technical one. It is just one of those things which is a concomitant of modern civilization. If this view is correct, electrolysis, like city noises, is an inevitable feature of a modern transportation system.

It must not be assumed, however, that unrestricted electrolytic corrosion should be condoned. On the contrary, a plea is made for a better understanding of the factors involved, so that an economical treatment may be applied in those cases where it arises.

Summary

This paper discusses the elements comprising the stray-current circuit and the electrochemical characteristics of these elements; and the need for an internationally standardized form of soil cell is indicated. Attention is then paid to the measurement of stray-current effects in the field and it is shown that there is no really satisfactory method by which the corrosion rate can be assessed with any degree of accuracy.

The paper then discusses the criteria which may be used as a basis for distinguishing between stray-current electrolysis and self- or chemical corrosion. Again, it is noted that, up to the present, no chemical tests have been devised to give a positive indication of the nature of the corrosion. Finally, the possibility of placing the subject upon an engineering basis in spite of the many uncertainties involved is discussed.

Elements of the Stray-Current Circuit

(*a*) Track Leakage

The literature upon stray-current electrolysis includes many papers dealing with the leakage of current from electrified rail systems. Thus, in August 1895, *Cassier's Magazine* made one of the first references to this subject. Michalke[1] was one of the first to treat it from a rational point of view, while McCollum and Logan[2] dealt with the subject mathematically upon the assumption that straight uniform tracks exchanged current with a homogeneous medium. Stubbings[3] treated track leakage from much the same angle and other writers[4–7] have extended the mathematical treatment. While some of these writers deal more specifically with inductive effects upon neighboring circuits, the method of approach is similar; namely, idealized conditions are assumed. Where it becomes necessary to introduce sweeping assumptions, the resulting conclusions may become quite unreal, and the present author submits that the very complicated cases met with in practice are not capable of even an approximate solution, mainly because the simplifications necessary for mathematical treatment are not permissible. In expressing this view, the author does not wish to detract in any way from the value of mathematical analyses, which, however unreal, do throw considerable light upon certain problems. For instance, the effect of track leakage resistance upon current in the earth (see page 14 of reference 2) is of considerable practical importance.

For the present, however, the discussion will be confined to a qualitative picture of the effect upon earth-potential gradients of the presence of an electrified track. Obviously, the general mass of earth forms a shunt path to the flow of current in the return rails, and the shape of the resulting "field" will depend upon the layout of the rail system, the potentials upon the rails from point to point, and the nature of the earth from place to place. Thus, under homogeneous soil conditions, and for a uniformly distributed load on a stub-end track fed by one substation, the equipotential lines would be approximately those shown in figure 1. Current flow in the earth would be normal to the equipotential lines, while any

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Essentially full text of an address presented at the Fourth Soil Corrosion Conference of the National Bureau of Standards, Washington, D. C., November 15–17, 1937, and used as the basis for a talk before the AIEE Washington Section, November 16, 1937.

C. M. Longfield is electrolysis engineer of the State Electricity Commission of Victoria, Melbourne, Australia. A native of Australia and a graduate of the University of Queensland, Mr. Longfield had experience with various enterprises in European countries and the United States during 1922–24, in accordance with the terms of a fellowship, and from 1925 to 1929 was employed by the New South Wales Government Railways and Tramways, resigning to take a position with the State Electricity Commission of Victoria.

The author wishes to acknowledge the assistance of R. J. Bennie.

1. For all numbered references, see list at end of paper.

irregularities in the soil would distort the diagram in much the same way as the signal strength of radio stations is affected by discontinuities in the surrounding terrain. The important thing to notice is the possibility of current flowing some considerable distance from the rail system. The potential gradient at any point remote from the track will obviously depend upon the loading, track leakage resistance, and other factors, and, therefore, upon this basis, there would appear to be no justification for the view expressed by many European writers that, provided a pipe or cable system approaches nowhere nearer than 200 meters to an electrified track, there is no danger of electrolysis. On the contrary, the author has measured appreciable traction currents in pipe lines which have been at least one mile distant from the nearest electric line. These currents were of sufficient magnitude to cause the corrosion which was noticed.

The stray-current field shown in figure 1 would be materially influenced by the addition of another substation. The spread of the stray currents is greatly reduced as substations are added to share the load. In fact, the potential gradient at any point in the earth varies very nearly inversely as the square of the substation spacing.

It may now be taken as established that the stray-current circuit of the track consists of a cell, made up of a steel rail elevated above earth potential, over a considerable length, and, therefore, becoming an anode or source of stray earth currents / soil A in contact with the anode // soil B in contact with / a steel rail which is negative to local earth and therefore forming a cathode. Following the method outlined by Evans (page 38 of reference 8) a filament of current i would be linked with the resistance R of the earth circuit and the electromotive force as follows:

$$iR = E_1 + E_2 - (P_c + P_A)$$

where

E_1 = the impressed electromotive force—in this case the rail drop between the anode and cathode ends of the circuit
E_2 = inherent or natural electromotive force due to differences in the metal of the rails at the two points or the soil (A and B) in contact with the anode and cathode
P_c = cathodic polarization
P_A = anodic polarization

Knowledge of whether the current in the earth is proportional to the rail potential for all values of that potential is important. From the preceding equation, it is evident that a change in R, P_c, or P_A will cause a change in i for a given E_1. The value of E_2 is likely to be small in practice.

Upon purely theoretical grounds, there is good reason to believe that P_c and P_A are negligibly small, that is, for all practical purposes. In the first place, the anode products from a steel rail should not induce anode passivity, and, in the second place, oxygen depolarization is likely to be very strongly in evidence at the cathode. Laboratory researches[9] show that this should be so, and field tests carried out by the author confirm this. Figure 2 is a reproduction of a record obtained close to a ballasted rail and indicates the simultaneous potential difference

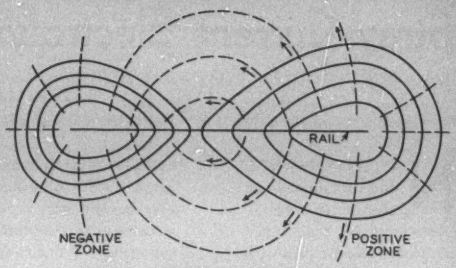


Figure 1. Equipotential lines in the earth

Solid lines indicate equipotentials
Dashed lines indicate current flow

between rail and earth and between two nonpolarizing electrodes placed on the ground in a line at right angles to the rails. The earth drop obviously is a measure of the current escaping to ground and it may be noted that perfect linear correlation exists between the rail potential and the earth drop (leakage current). That linear correlation does not always exist is evident from figure 3, which illustrates a similar chart obtained on a buried steel water main. Polarization is strongly in evidence, due, no doubt, to the absence of oxygen depolarization.

It may now be taken as established that, for all practical purposes, the leakage current is proportional to the rail potentials, though this would not necessarily be so if the rails were composed of metals other than mild steel, for example, copper or chrome-nickel steel.

(*b*) Currents in Pipes and Cables

Consideration of the effect of the presence of underground metalwork upon the stray-current field is now necessary. In the first place, the presence of lead-covered cables is not likely to increase the leakage current appreciably, nor will the presence of large steel mains do so except in some special cases. Thus, for all practical purposes, the buried pipe or cable may be considered as a leaky conductor lying in a potential field of more or less uniform gradient, depending upon the position of the conduit with respect to the tracks. The implications, as regards current in the conduit, arising from this conception, were carefully considered in a previous paper.[10]

Now, as Evans has shown on page 25 of his book,[8] the stray-current circuit is expressed by two cells, namely,

rails / wet ground / pipes (or sheaths)

balanced by

pipes (or sheaths) / wet ground / rails

or alternatively,

Fe (anode) / soil A / metal x (cathode)

balanced by

metal x (anode) / soil B / Fe (cathode)

The amount of corrosion taking place will depend, other things being equal, upon the current density at the

anode of metal x; and this, in turn, will depend upon the conductivity of the conduit (metal x), its leakage resistance, the polarization of the anode or of the cathode, or of both and the impressed potential. A first approximation, the last-mentioned potential is independent of the presence of the conduit in the leakage circuit and, on this account, and for the reasons stated above, it is therefore proportional to the rail potential. Upon purely theoretical grounds, then, assuming a corrosion efficiency of 100 per cent at the anode (a reasonable enough assumption in practice), the amount of corrosion is proportional to the rail potential assuming that polarization of the underground metal is negligible. But, there are several factors which enter to spoil the application of any generalizations in this regard, that is, although simple proportionality exists in any given case, the same rail potentials in two different cases do not connote equal stray-current hazard. This statement applies, not only to over-all rail drop and to rail gradients, but also to the potential difference between buried conduit and rail. This is unfortunate, if for no other reason than that designers of electric traction systems cannot predetermine the corrosion hazard with any degree of certainty.

Among the factors which interfere with any such generalization are to be noted the inhomogeneity of the soil, configuration of the conduit and rail systems, nonuniformity of the leakage resistance of the conduit with respect to ground, also of the rail bed, and, of course, polarization. Any one of these is, in itself, sufficient to modify the corrosion hazard; and, the difficulties in allowing for variations in these factors in a mathematical treatment are so great that the writer has been unable to place any degree of confidence in that form of analysis.

It is necessary, now, to hark back to the conception of the stray-current circuit as consisting of two cells—one balancing the other. As has been said, the amount of

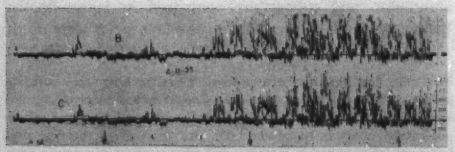


Figure 2. Correlation chart showing potentials of rail B and earth C

Polarization not present

stray current in the earth is proportional to the rail potentials in any given case. As far as buried metalwork is concerned, then, the corrosion circuit* is:

metal x (anode)/soil B // soil A / metal x (cathode)

The presence of soils A and B will tend to set up "long line" currents, and will produce potentials which will enter into field measurements as a steady displacement of unknown amount. As a consequence of this conception of the corrosion circuit, the potential difference between rail and conduit is of little real significance as it is measured over part of the circuit only; but the characteristics of the cell:

metal x / soil B // soil A / metal x

are of profound significance. If it can be shown, for instance, that the cell is reversible or that it is easily polarized, then considerable light will be thrown upon the susceptibility to corrosion of the metal comprising the conduit.

(c) Volt-Ampere Characteristics of Soil Cells

Many writers[11–13] have referred to the possibility of conducting accelerated tests upon the corrosiveness of

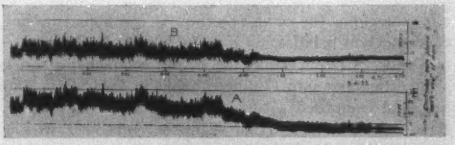


Figure 3. Correlation chart showing potentials of pipe A and earth B

Polarization present

soils. In particular, Blum and Rawdon[11] have put forward the thesis that the volt-ampere characteristics of corrosion cells are a satisfactory index of susceptibility to chemical corrosion. These experimenters went so far as to state that:

"The fact that it takes a much higher potential to cause the copper to corrode than the zinc, is much more significant in predicting relative corrodibility than the fact that, because copper dissolves with a valence of one, twice as much copper as zinc is dissolved by a given current."

The shape of the volt-ampere characteristic as revealing film breakdown, or hydrogen overvoltage, should be significant as an index to corrodibility. But, as Evans points out (page 650, reference 8), the driving potential arising from "natural" effects is not easy of determination. However, as a measure of stray-current hazard, the volt-ampere characteristic should be of considerable importance. I. A. Denison[13] shows that there is some connection between laboratory results obtained by this means and field tests; and the soil cell used in his work might, with advantage, be accepted as an international standard so that the work of experimenters operating in different countries could be compared.

It must be pointed out that short-period tests may not give a satisfactory indication of long-period corrosion, since the stifling action of the products of corrosion which may be deposited near the anode will not be apparent in the short run. However, stray-current corrosion generally removes the end products some distance from the anode

*This is a fiction only to the extent that the current does not circulate through a closed path consisting of metal x and the earth; but the destination or the origin of the stray current does not matter in considering the behavior of a metal wholly insulated from other metalwork.

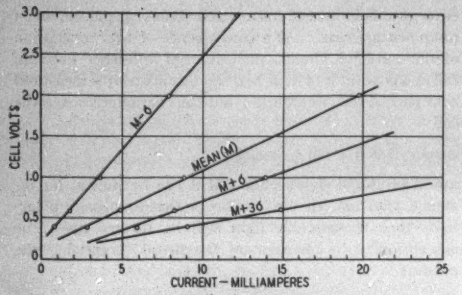


Figure 4. Volt-ampere characteristics of mild steel in 17 classes of soils

σ = standard deviation

and, therefore, the same objection is not apparent, but concentration polarization may be important. Unaware of Denison's recent work, the author conducted a series of investigations into 17 different soils in Australia. The cell used comprised a tubular anode four inches long by three-eighths inch external diameter embedded in soil moistened by distilled water to a uniformly wet consistency without flooding and contained in a three-inch internal diameter cylindrical pot of the same metal as the anode. The cells were set up and allowed to stand for 24 hours before readings were made. A steady known potential was applied across the cell, and one minute later the current through the cell was measured. Observations were made with an ascending and a descending scale of potentials. The pH values of the soil ranged from 5.2 to 9.2. In particular, soil A ran 9.2, soil B 7.0, and soil C 5.2.

Figure 4 sets out the results of tests of this nature on mild-steel electrodes. Current density was not used as a basis since the anode and cathode areas were not equal. In stray-current zones, the area of the cathode is likely to be many times the area of the anode. No correction was made for IR drop in the soil. As there was considerable dispersion about the mean value of current at any potential, the standard deviation was determined, and the results have been assembled to show the effect of this dispersion. Thus, the probability is of the order of 100 to 1 against encountering a soil which would give a value to the right of the line $M + 3\sigma$.

While the characteristic shown in figure 4 is not directly comparable with similar data published by other writers, it does throw a good deal of light upon the behavior of mild steel in a stray-current environment. For instance, it confirms what has been said before, that a linear relation exists between applied potential and resulting current when mild-steel electrodes are used. There are exceptions to true linearity, as was noted in connection with figure 3; but, in the author's extensive experience, these are rare; and, in any case, stray traction currents are generally rapidly fluctuating, and often reversing in direction as well, so that it is reasonable to expect, upon purely theoretical grounds, that polarization would not be very marked. Be that as it may, the results now being discussed are strictly comparable among themselves; and the conclusions about to be drawn are not invalidated by the presence or absence of polarization.

The next series of investigations were carried out on 18-per-cent-chromium 8-per-cent-nickel steel (Staybrite) under conditions identical with those just described. Soils from the same locations were used and the results have been collected as before by determining the mean

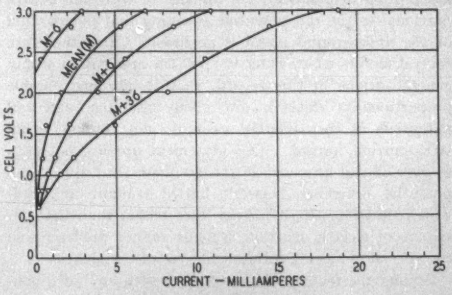


Figure 5. Volt-ampere characteristics of chrome-nickel steel in 17 classes of soils

σ = standard deviation

current and the standard deviation at any applied potential. As may be seen from figure 5, there is a threshold potential* somewhat in excess of 0.5 volts. Above this potential, corrosion, as revealed by the amount of current passed through the cell, proceeds, at first slowly, and then, with the higher voltages, at about the same speed as in the case of mild steel.

As a matter of interest, the characteristics of lead, zinc, aluminum, and copper are compared in figure 6. In these cases, soils A, B, and C of the first series were used.

The conclusions to be reached from these test results are:

Mild steel, lead, and zinc are susceptible to attack by stray currents of any magnitude, however small. Copper is less susceptible, and aluminum, on the face of it, appears to be relatively immune at low potentials. As was to be expected, Staybrite gives the best performance of the metals tested; and this result is consistent with others which the author carried out in which potentials of different amounts were applied to a number of soil cells for an extended period. The corrosion rate of Staybrite was comparable with that of mild steel at high potentials; but, at low potentials, no corrosion was measurable after one month's electrification.

Thus, it would seem that the type of metal used for pipes and cables has a very important bearing upon the hazard to which underground metalwork is subjected in an electrolysis area.

(*d*) Variations in the Leakage Path

So far, it has been assumed that the leakage path has been uniform. The introduction of discontinuities, such

*The possibility of this occurring was suggested to the author by Doctor W. H. Hadfield. The subject has recently been traversed in some detail by Doctor S. Brennert in a paper before the Iron and Steel Institute.

as would be caused by variations in the nature of the soil from place to place, and even by the addition of a protective coating on a pipe or cable, is sufficient to modify very profoundly the effect of a stray-current field upon the location of anode areas on buried metalwork, and upon the current density of discharge. These factors may easily render abortive any attempt to reduce the problem to a mathematical basis. In an earlier paper[10] the author discussed the effect of variations in the electrical resistance of the pipe coating, while the factors underlying pitting have been discussed by Shepard.[14] Pipe coatings will not be discussed here, but some attention will be given to variations of potential gradient in the soil.

That the stray currents leaking from electrified tracks migrate some distance from the rails has already been shown. The effect has been so marked that, in many instances, this fact has caused the removal, from the neighborhood of electrified tracks, of observatories carrying out fundamental researches into terrestrial magnetism. The distribution of such currents has been considered by many writers,[15] and the author's investigations confirm the general notions expressed in the discussion of figure 1. For instance, an investigation, carried out on ballasted railway tracks, showed that the potential gradient at

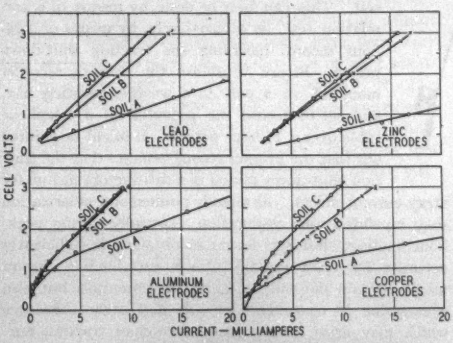


Figure 6. Volt-ampere characteristics for four metals and three soils

right angles to the track was at first very steep, and then after 60 or 80 yards, it flattened out very considerably. Figure 7 shows the results of one such test. In this case, the potential difference between a stationary earth electrode *A* near the rails and a moving earth electrode *M* was plotted against a simultaneous record of potential difference between rail and earth. The ratio, then, shows the earth drop per volt between rail and earth. It might be pointed out that a check was made with both *A* and *M* moving away from the track and the test was stopped when correlation between the potential difference of *A*-*M* and rail-earth ceased to be good. At a distance of 2,000 feet, leakage from another track produced interference which prevented exploration beyond that distance.

It will be seen that, although a very pronounced "hump" occurs close to and under the track, the potential gradient is not inappreciable even at 2,000 feet, where it is of the order of 6 millivolts per 1,000 feet per volt between rail and earth. As it is possible for this type of rail to be 50 or even 100 volts positive to earth, it is possible to find gradients of one millivolt per yard some half mile from the rails. Potential gradients of this magnitude have been observed by the author, and it is not surprising that, under such conditions, large steel pipes are subjected to electrolysis attack even though they do not approach within half a mile or so of the track.

This consideration naturally leads on to those cases where changes in the soil, either from some geological influence or from changes in level, produce highly conducting soil pockets. A soil-resistivity survey will reveal irregularities of this nature, while the occurrence of faults often confirms the findings of the soil survey. Figure 8 is particularly interesting in this regard. It may be noted that corrosion faults occur exclusively in low-resistivity soil pockets. The electric track under notice was in an outer suburban area, and, therefore, lightly loaded. The rails between substations exhibited a tendency to remain negative to earth for long periods, during which current flowed off the pipes over a wide area. Trains in motion

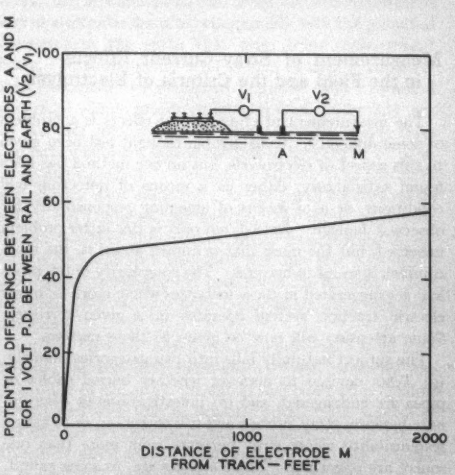

POTENTIAL DIFFERENCE BETWEEN ELECTRODES A AND M FOR 1 VOLT P.D. BETWEEN RAIL AND EARTH (V_2/V_1)
V_1
V_2
A
M
DISTANCE OF ELECTRODE M FROM TRACK — FEET

Figure 7. Earth potentials due to ballasted track

near the junction caused current to flow from that point both east and west to the detriment of the pipe system. Leakage from the pipes was naturally heaviest at the points of low soil resistivity.

Conditions such as these make it impossible to apply a highly refined mathematical analysis. The electrolysis engineer is, therefore, thrown back upon field measurements as a means both of assessing the electrolysis hazard and of devising mitigative measures.

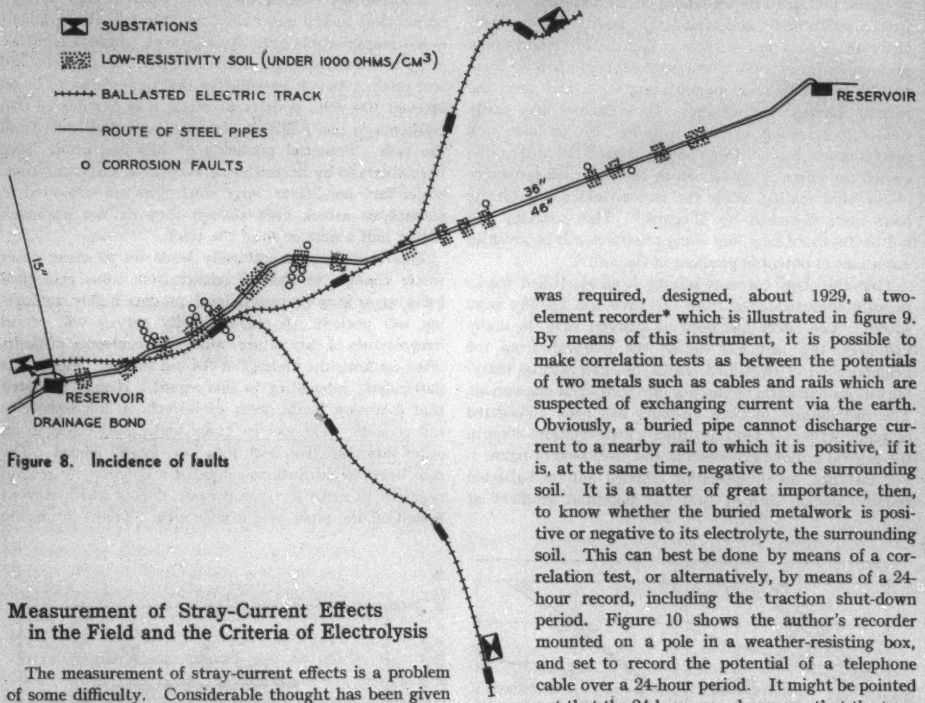


Figure 8. Incidence of faults

Measurement of Stray-Current Effects in the Field and the Criteria of Electrolysis

The measurement of stray-current effects is a problem of some difficulty. Considerable thought has been given to this aspect of electrolysis, but no one method has been found satisfactory, either as a means of detecting bad conditions, or as a means of assigning responsibility for observed damage. Indeed, not only is this latter problem unsolved, but the more that is known about it, the more complex it seems to become. The complexity of the problem is exaggerated in those instances where more than one electric traction system operates in a given territory. Some attention will now be given to these matters.

The subject naturally falls into two categories, namely, (*a*) Tests devised to discover whether buried cables or pipes are endangered, and (*b*) investigations to discriminate between stray current and soil corrosion, or to assign responsibility where stray currents from more than one source are operating. These aspects are, to some extent, complementary; but, as far as possible, they will be considered apart.

(*a*) Electrolysis Surveys (Electrical Tests)

Potential Tests. In making field surveys to discover whether a buried pipe or cable is endangered, the most obvious test is a potential survey. Owing to the presence of electrode and polarization potentials in the stray-current circuit, potential readings between buried conduit and rail may be quite misleading as indicating the corrosion hazard or even the destination of stray currents. The author, in realizing that something much more definite was required, designed, about 1929, a two-element recorder* which is illustrated in figure 9. By means of this instrument, it is possible to make correlation tests as between the potentials of two metals such as cables and rails which are suspected of exchanging current via the earth. Obviously, a buried pipe cannot discharge current to a nearby rail to which it is positive, if it is, at the same time, negative to the surrounding soil. It is a matter of great importance, then, to know whether the buried metalwork is positive or negative to its electrolyte, the surrounding soil. This can best be done by means of a correlation test, or alternatively, by means of a 24-hour record, including the traction shut-down period. Figure 10 shows the author's recorder mounted on a pole in a weather-resisting box, and set to record the potential of a telephone cable over a 24-hour period. It might be pointed out that the 24-hour record assumes that the traction shut-down period is a satisfactory datum for stray-current effects. As already pointed out, polarization may invalidate this assumption, especially during peak-hour loading; but the datum so obtained is sufficiently accurate for most practical purposes. Such a datum might contain not only polarization potentials but also effects due to concentration cells and other influences which may arise from causes other than traction currents, or, at any rate, from secondary effects of leakage currents.

Correlation tests, on the contrary, do give a true indication of the traction component of any electrical effects operating. Thus it will be found, in general, that the time-potential characteristic of the pipe bears a simple relation to the time-potential characteristic of the nearby rail. The relation would be of the form:

$$V_p = kV_R + E$$

where

V_p = potential difference between pipe and reference electrode
V_R = potential difference between rail and reference electrode
E = resultant electrode potential including polarization
k = a constant

* This instrument consists of two Tinsley stretched suspension reflecting type galvanometers, mounted to register on sensitized paper which is wrapped on a clock work-driven drum. The galvanometers have a period of about two seconds and a sensitivity of about 1,000,000 ohms per volt. The range is from 0.3 millivolts to 6 volts without external devices.

This method of analysis is valid only if the rail potential is large compared with the algebraic sum of the electrode potentials present in the circuit. Such a test, with proper safeguards in respect to the position of the reference electrodes, is an infallible indication for interchange* provided the metals tested are not perfectly insulated from earth at the point of test.

Where two or more rail systems influence the pipe potential, the equation quoted above becomes, in general,

$$V_p = k_1 V_{R1} + k_2 V_{R2} + k_3 V_{R3} + \ldots + E$$

And, by taking a number of observations, values of the constants k_1, k_2, etc., may be calculated from the simultaneous equations.

Potential tests of this nature are, however, purely qualitative, since the current discharged from the buried metal will depend just as much upon the resistance of the path between buried pipe and rail as upon the effective potential across the circuit.

Current Tests. Since the corrosion rate is dependent upon the current density, anything which will modify the discharge of current, such as flaws in an insulating coating, will also modify the relation between potential difference across the "cell" and corrosion rate. The best measure of corrosion rate then is current density, but this varies so much from point to point that the discovery of the "worst place" becomes a matter of the utmost difficulty. Notwithstanding this, there have been very many methods discussed for the direct or indirect measurement of the current density at the anode.[17–19] The French investigators have relied upon measurements carried out on the undisturbed surface of the soil, while the earth-current meter developed by McCollum and Logan requires excavation around the pipe under test.

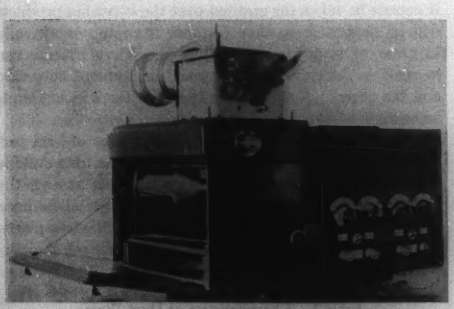


Figure 9. Two-element recorder with cover removed

Both of these methods are dependent upon nonpolarizing electrodes to make contact with the soil at two or more points. Copper-sulphate electrodes are advocated. The author has tried many types of nonpolarizing electrodes, including copper-sulphate ones, but he is not convinced that satisfactory results can be secured by this means. It is, of course, true that certain solutions, like potassium chloride, can be chosen so that liquid-liquid partition potentials will be a minimum; but, unfortunately, the residual potentials even on well-constructed pairs of electrodes are often comparable with the potential differences in the earth that arise from stray-current effects. In short-period tests of this nature, it is, therefore, impossible to eliminate unknown and unwanted potentials. This means that observed potentials are not absolute, and, indeed, it is impossible to decide from such data whether a buried conduit is discharging or picking up stray current. The author believes that this criticism applies with equal force to the earth current meter and to the Schlumberger method. At most, such tests disclose whether the conduit under examination is exchanging current with the earth, but they give no positive information concerning the polarity of the conduit. This is a great pity, because both methods are otherwise very attractive.

Figure 10. Recorder mounted on pole

Another method[20] which has been advocated from time to time, is the differential-current test, whereby the magnitude of the stray current at one point on a conduit is compared with that at another point. The success of this method depends upon the accuracy, both of the instruments used, and of calibration of the test lengths. In general, the method fails in those cases where, for instance, several cable sheaths are bonded together. As it depends upon the measurement of the difference between quantities nearly equal in magnitude, the necessary degree of accuracy is hard to attain in field experiments. The method can be further criticized in that it does not reveal "hot spots," but indicates only the average current lost over an appreciable length.

Beck[21] has advanced a novel method which requires the attachment of coupons to the pipe under test. The method appears to give satisfactory results where it can be applied conveniently.

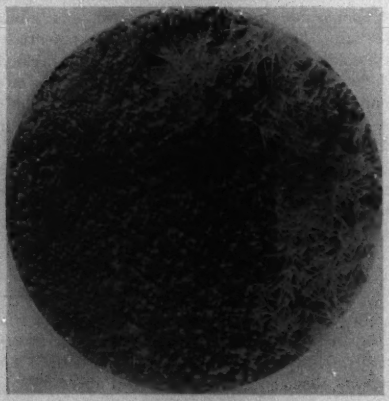
The present author has experimented with very many

* This matter and its relation to the design of drainage bonds are discussed in a recent article.[18]

methods; but these suffer from the same disadvantages as those just mentioned, namely, the "hot spots" cannot be readily determined.

The author is of the opinion that there is no satisfactory field test by which the *rate* of corrosion can be determined. Qualitative tests can be applied, both to determine whether a buried pipe or cable is anodic to its electrolyte, and to determine the origin or destination of the stray currents. Tests of this nature, limited as they are, do, however, form a useful basis for the design of mitigative measures. But another point has often to be settled, namely, has observed corrosion been caused by stray currents or by chemical agencies? It should be obvious from what has been said that all that electrical tests can do is to show whether a buried pipe or cable is anodic or cathodic. Where special arrangements can be made, the current density of discharge from the pipe or cable can be measured; and this would certainly indicate that stray-current corrosion had occurred. The mere determination of polarity is not enough in itself to exclude chemical corrosion as being the predominating if not the only agency at work. To discriminate between stray current and soil corrosion, electrical tests must be supplemented by chemical tests.

(*a*)—Full size



(*b*)—Section magnified eight times

Figure 11. Anode deposit in duct water A

(*b*) Electrolysis Surveys (Chemical Tests)

Perhaps the most vexed question in underground corrosion in an electric-traction zone is this question of deciding between soil action and stray-current effects. It has two aspects. Firstly, the owner of affected conduits wishes to allocate responsibility, and that cannot be done by the simple, but erroneous, means suggested in one example.[22] Secondly, the impartial electrolysis engineer wants to know whether the mitigative measures he has introduced have been effective or not. An understanding of the factors involved is highly educative; but the matter is not merely of academic interest.

Since chemical corrosion in an aqueous environment at ordinary temperatures is an electrolytic process, the same process is at work here as in stray-current corrosion. There are, however, differences in the disposition of the anodes and cathodes, and often, in the rate of attack. Generally speaking, the anode and cathode are close together in chemical attack, though it is true that highly conducting conduits such as welded steel pipes may conduct "long line" currents arising in differences in soil composition from place to place. Differences of this nature in moisture, salt, or oxygen content, make tests on small specimens somewhat unreliable. This sort of thing, as well as many other complex factors, make investigations into chemical attack very difficult. Thus, it cannot be taken for granted that the corrosion products will be deposited at some distance from the anode only in cases of stray-current corrosion. What criteria can be used in discriminating between one type of corrosion and the other? A simple question, but there is no simple answer.

It was once thought[23] that the appearance of lead peroxide on a corroding lead cable sheath was an infallible indication of the presence of stray currents, though the converse was not necessarily true. This has since been disproved.[6] Both Evans[3] and Haehnel[24] lay emphasis upon the significance of the chlorine content of the cor-

Table I. Characteristics of Duct Water

Liquid	Chemical Constituents	Proportion (Parts per Million)	pH	Resistivity (Ohms per Cubic Centimeter)
A	Calcium bicarbonate	100	5.8	Not recorded
	Sodium chloride	350		
	Nitrates	trace		
B	Sodium bicarbonate	650	8.4	1,800 at 20 degrees centigrade
	Sodium chloride	50		
	Sulphates	trace		
C	Sodium bicarbonate	260	6.7	3,300 at 20 degrees centigrade
	Sodium chloride	10		

rosion products. Haehnel assumes that chlorides are found in all types of ground, and that, generally, the chloride content of normal ground does not exceed 0.05 per cent. In the paper referred to, Haehnel makes the statement that, in self-corrosion in the earth, lead carbonate, basic carbonate, lead oxide, and lead hydroxide arise as corrosion products, while stray-current electrolysis produces lead chloride, lead sulphate, or even lead nitrate. Furthermore, with regard to the quantity of chloride present, Haehnel says that quantities up to 4 per cent can arise secondarily through conversion of lead carbonate with earth water; so that, it would be assumed, quantities in excess of 4 per cent may be regarded as indicating stray current attack.

The author has not carried out sufficient investigations into matters of this nature to be able to express a definite opinion; but the following somewhat elementary experiment may be of interest. Sheet-lead electrodes prepared from commercial lead cable sheathing were suspended vertically in duct waters, and direct current was passed for about two weeks, after which, the electrodes were examined. The anode current density was just under 2 milliamperes per square decimeter. The liquid was open to the air, and the test was conducted at room temperature. Table I sets out the characteristics of the duct water used.

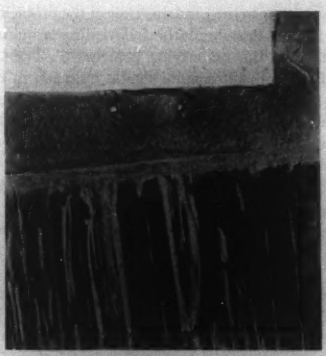
The type of end product to be expected in any given case must surely depend upon the nature of the duct water. This is amply brought out in the investigations under notice. Figure 11*a* shows part of the anode in liquid *A*. A heavy incrustation of lead carbonate, overlying, in some parts, crystals of lead chlorocarbonate is clearly visible. The photomicrograph shown in figure 11*b* does not, unfortunately, reveal the latter crystals, but the pattern of the lead-carbonate deposit is easily distinguishable. Examination of pits by means of a binocular microscope showed that the chlorocarbonate crystals were definitely more closely associated with the actual corrosion than were the carbonate crystals which were growing out from the anode.

The cathode appeared to the naked eye to be unaffected, but microscopic examination showed that clear crystals, apparently of calcium carbonate, had been deposited.

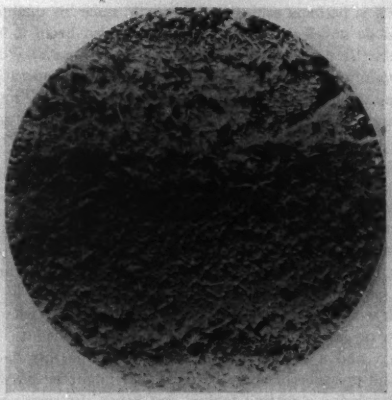
Figure 12*a* illustrates the anode in liquid *B*. This cell was subjected to the same treatment as cell *A*, but the effect of the different electrolyte is most marked. In this case, streaks of lead carbonate and lead peroxide are in evidence. Figure 12*b* shows a photomicrograph of a portion of this anode. In this case, the deposit is much more compact, and easily flakes off in patches leaving a clean, bright etched lead surface.

The third cell, whose anode is illustrated in figures 13*a* and 13*b* is again different from the others. The low salt content has the effect of greatly reducing the incrustation of products which appear in the original as small isolated craters surrounded by reddish patches, presumably, of lead monoxide and possibly of lead peroxide. Since the same current flowed through all three cells in series, the same amount of corrosion might be expected in each. This was not checked, but, as Haehnel points out in the paper quoted above, the nature of the electrolyte will have an important influence upon the corrosion efficiency; and the indications are that anode *A* suffered the greatest attack, due, no doubt, to the relatively high chlorine content of the electrolyte.

Looking at the matter broadly, it seems to resolve itself into this: that the end products will be determined by (*a*) the composition of the electrolyte, and (*b*) the current density. With regard to (*a*), cognizance might have to be taken of the extent to which differential aeration was also operating. As an alternative to the current density, it might be more satisfactory to include the potential drop at the metal-liquid interface, since, in the cases illustrated in figures 11, 12, and 13, the same current density produced three quite different results. Thus, it might be said that corrosion occurred on an anode where so many



(*a*)—Full size



(*b*)—Section magnified ten times

Figure 12. Anode deposit in duct water B

watts per square decimeter were dissipated. This energy basis has the further merit of linking the electrical energy with the chemical energy of formation of the end products.

The Engineering Approach to Electrolysis Mitigation

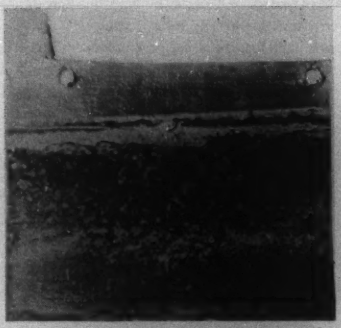
By this phrase, the author wishes to imply that the mitigation of stray-current corrosion can be placed upon the same basis as other engineering problems. That is to say, inquiry into the fundamentals of the problem should first be made; this should be followed by a quantitative formulation of the underlying principles. Then, in the practical case, measurements should be made in the field just as is done by surveyors or hydrographers. Then comes the formulation of measures designed to meet known conditions, proper account being taken of the cost—annual and capital—of the alternatives proposed. And finally, a check should be made of the results of the measures adopted.

Taking these points in turn, it is noted that the fundamentals of stray-current corrosion are matters for the physical chemist; and it is therefore necessary for the electrolysis engineer to link himself with research workers in this field of inquiry. There is nothing new in this, since the bridge engineer is just as much dependent upon the chemist and physicist as is the electrical engineer.

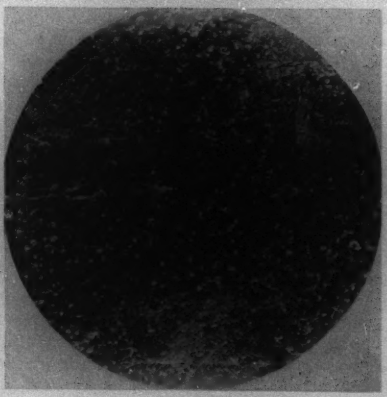
It is necessary, then, for the electrolysis engineer to be informed upon all aspects of the corrosion problem, which is perhaps asking rather much, since his qualifications as an electrical engineer should also be of a high order. In particular, he should have more than a nodding acquaintance with electric-traction design and operation. Thus, the best arrangement would appear to be the maintenance of a close liaison between the electrolysis engineer and a physical chemist. Assuming that this is done, it must then be assumed that the characteristics of the soil in a given area are carefully determined, so that the occurrence of "hot spots" can be made known to the traction authorities as well as to the owners of buried metalwork. Scott Ewing has shown, in a recent paper,[25] how this sort of information may be used to determine the corrosion hazard. The constants referred to in his work would be materially modified in those cases where a more or less effective coating had been applied to the pipe; and a further modification would be introduced by the presence of stray currents. It might be possible to determine a pitting factor, and hence the number of perforations per annum per unit area, even under these special conditions, by means of carefully conducted tests on buried specimens charged to varying potentials with respect to the ground. Much research is needed along these lines, and it should result in a reasonable estimate of the cost of repairs at a particular spot. The amount of money that it would be economical to spend upon mitigative measures could then be ascertained.

These thoughts apply to new construction; but, more often than not, the electrolysis engineer will be faced with a situation where corrosion is occurring on existing conduits. Closer estimates of annual costs of repairs can be made in this case. From this point, the engineering solution of the problem is typical of most engineering problems, that is, the costs of various alternatives are computed, and the least expensive is chosen, due regard being paid to all the factors involved.

In the author's limited experience, the conclusion[26] has been reached that, as the reduction of rail potentials can result only in a somewhat proportionate decrease in the corrosion rate, electric drainage sooner or later must be resorted to as a means of removing anodic areas from buried metalwork. These remarks may apply also to the use of insulating joints. In any given case, even if the results of drainage cannot be predicted, it is very inexpensive compared with other alternative means and the results of its application can very easily be checked.



(*a*)—Full size



(*b*)—Section magnified ten times

Figure 13. Anode deposit in duct water C

Although it is possible to put this subject on an engineering basis in the manner indicated, consideration by those best able to judge will show that a high degree of

accuracy is not attainable, but the errors and the unknowns will be reduced to a minimum if the problem in any given city is handled by a co-operative committee upon which all the interested utilities are represented.

Concluding Remarks

In conclusion, the author would like to emphasize one point in connection with this subject. U. R. Evans has pointed out that corrosion-research engineers are very willing to co-operate in the exchange of information dealing with their own discoveries; nevertheless, there is still a marked reluctance on the part of some bodies to discuss electrolysis. This is to be deplored, since an adequate handling of the problem can be undertaken only when all interested parties frankly disclose the condition of their own plant. The author is perhaps particularly fortunate in his relations with the Melbourne Electrolysis Committee; and the benefits that have flowed from mutual understanding between the public utilities in that city are reflected in the results achieved.

If the author's thesis be accepted, namely, that any potential difference, however small, will cause current to escape from a steel-rail system, then the electric-traction authority is not guilty of negligence in the operation of the railways merely because current leaks into the ground. Current leakage is an inevitable condition of the operation of the system.

If this view be accepted, then surely the problem becomes purely a technical one, capable of solution only when all the factors operating in a given case are known. The author advances no suggestions as to a fair apportionment of the costs of mitigative measures, whether applied to the traction system, or to the buried metalwork, before or after laying.

If the threshold potential of chrome-nickel steel is as significant as the author believes it to be, then every endeavor should be made to bestow the same characteristics upon lead, and, in certain situations, upon cast iron as well. If that could be done, the problem would be susceptible of much more effective treatment than it is at present.

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Education and Business Leadership

Data on 54,000 officers of some 500 typical industrial companies show that: "A college-trained man is 18 times as likely to be president of an industrial company as is a noncollege man. He is 12.5 times as likely to be treasurer, twice as likely to be in charge of production, 18 times as likely to be an engineer, and 12 times as likely to be a sales official. Taking all these officers together the college man is seven times more likely than the noncollege man to be one of them.

"If we examine the influence of the type of college in which the education was secured, we find the following results which, at first glance, are decidedly startling. In one group we consider those who were educated at an engineering or technical college, and in the other group those who attended any other type of college such as liberal arts, law, business, and the like. Here we find that an engineering-college man is 12 times more likely to be found in the presidential position than if he had attended a nonengineering college. He is 5 times as likely to be treasurer, 30 times as likely to be in production, 174 times as likely to be in engineering, and 24 times as likely to be in sales. Grouping all offices together, an engineering-college graduate is 30 times as likely to find himself an officer in American industry as is a graduate of a nonengineering college.

From an article of the same title by Karl T. Compton (F'31) president, Massachusetts Institute of Technology, Cambridge, and published in the November 1937 issue of *Mechanical Engineering*, pages 841-3.

News

Of Institute and Related Activities

The Edison Tower to Be Dedicated

On February 11, 1938, The Edison Tower at Menlo Park, N. J., shown on the front cover of this issue, will be dedicated, according to an announcement by James Burke (A'93, F'13, member for life), president of the Edison Pioneers. On that day, which marks the 91st anniversary of Thomas Alva Edison's birth, the giant replica of his first practical incandescent lamp will be lighted when a button is pushed at the annual luncheon meeting of the Edison Pioneers in New York, N. Y., 30 miles distant from the tower, and thereafter it will be lighted nightly.

The Edison Tower is to be presented by William Slocum Barstow (A'94, F'12, Life Member), president of the Thomas Alva Edison Foundation, Inc., to the foundation in behalf of the Edison Pioneers, of which he is honorary president. The tower was built as a lasting reminder of the many achievements of Edison at Menlo Park during the decade extending from 1876 to 1886, and replaces the temporary steel tower that was erected during "Light's Golden Jubilee" in 1929. It is located on the site of his original laboratory there, and marks the exact spot where the first practical incandescent lamp was born on October 21, 1879.

Precast concrete slabs form the face of the tower, growing lighter in color toward the top where a light blue shading will provide an effective contrast with a glass bulb almost 14 feet high and 9 feet in diameter at the widest part, and containing 153 pieces of amber-tinted Pyrex glass two inches thick. The glass will produce a sparkling effect under the sun, and will be illuminated at night by three sets of light bulbs totaling 5,200 watts. Flood lighting also will be used at night on the structure, which is 131 feet high over-all. Within an enclosure of black granite set at ground level, a perpetual light will be fed by current from several sources to guard against failure of any one. The perpetual light, a replica of his first lamp, was switched on October 21, 1929, by Mr. Edison from Dearborn, Mich., and has been maintained uninterrupted. It was unharmed by the lightning which on August 12, 1937, demolished the temporary steel tower. A bronze door with plate glass in one of the sides of the octagonal base of the tower permits a view of the "Eternal Light" room; on each of the other seven sides is a bronze tablet on which inventions made by Edison at Menlo Park are described.

Commemorative of Edison's invention in 1877 of the phonograph, the tower also is equipped with a modern sound system containing two sets of loud-speakers, one group just above the base and a second group 96 feet above the ground. Coincident with the dedication ceremony in New York, the initial program of electrical transcriptions over The Edison Tower sound-equipment installation will be broadcast at Menlo Park in the early afternoon of February 11.

Winter Convention Report Planned for March Issue

The 1938 AIEE winter convention is under way at New York, N. Y., as this issue of ELECTRICAL ENGINEERING goes to press. Attendance at technical sessions and social events shows this meeting to be highly successful. The registration on the first day was 548 compared with 470 in 1937, 602 in 1936, and 633 in 1935. On the second day 479 registered, compared with 357 in 1937, 444 in 1936, and 301 in 1935.

The convention and its various features are scheduled to be reported completely in the March issue.

1938 Washington Award for F. B. Jewett

Frank Baldwin Jewett has been selected to receive the Washington Award for 1938, according to an announcement from the Washington Award Commission. Doctor Jewett is vice-president of the American Telephone and Telegraph Company, and president of the Bell Telephone Laboratories, Inc., New York, N. Y. A biographical sketch of Doctor Jewett may be found in the "Personal Items" section of this issue.

No date as yet has been set for formal presentation of the award, which consists of an inscribed bronze plaque mounted upon a marble base. The award is given annually, when deserving candidates are found, by the Washington Award Commission as "an honor conferred upon a brother engineer by his fellow engineers on account of accomplishments which preeminently promote the happiness, comfort, and well being of humanity." The commission is composed of 18 members, representing the following five engineering

During the third annual reunion meeting of the General Electric Test Alumni Association at Schenectady, N. Y., an oil portrait of A. L. Rohrer (A'87, M'88, member for life) retired, "grand old man of test," was presented to the Edison Club in that city. The group shown here are, left to right: L. B. Bonnett (A'18, M'25) purchasing agent, Brooklyn Edison Company; C. F. Pittman, General Electric Company; H. M. Mott-Smith, artist who painted the portrait; Mr. Rohrer; J. S. Wise (A'96, M'27, member for life) president, Pennsylvania Power and Light Company; C. L. Proctor (A'08) vice-president and general manager, Toledo Edison Company; and R. C. Muir (A'08, F'36) engineering vice-president of the General Electric Company and president of the test alumni association

societies: American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers, The American Society of Mechanical Engineers, AIEE, and Western Society of Engineers.

The award was founded in 1916 as the outgrowth of an endowment and suggestion by John Watson Alvord of Chicago that there should be some means of recognizing outstanding engineers who render pre-eminent service in promoting of public welfare. The idea was proposed originally to the Western Society of Engineers, which soon invited the other societies to participate in the award. They accepted, and the award has since come to be recognized as one of the highest honors that can be conferred upon an American engineer.

Since the first award was conferred in 1919, several years have intervened in which no award was made, because the commission discovered no candidate that seemed eligible for the high recognition. Members of the AIEE who have previously received the honor are: Herbert C. Hoover (HM'29), M. I. Pupin (A'90, F'15, HM'28, past-president, deceased), B. J. Arnold (A'92, F'12, HM'37, member for life, past-president), W. D. Coolidge (A'10, F'34), Ambrose Swasey (HM'28, deceased), and C. F. Kettering (A'04. F'14).

Membership—

Mr. Institute Member:

You are proud to be able to say, "I am a member of the American Institute of Electrical Engineers."

Won't you devote the next ten minutes of your time to writing down the reasons for being a member? Please, *do it now!*

Surely, you meet at least one man a month who is not a member of the Institute but should be. Tell him why you are a member.

If he is interested, send his name to the membership chairman of your Section.

A. S. Anderson

Vice-Chairman, District No. 4
National Membership Committee

Memorial Tablet Unveiled for Calvin W. Rice

A bronze tablet to the memory of the late Calvin Winsor Rice (A'97, F'12) was unveiled during the annual meeting in December 1937 of The American Society of Mechanical Engineers, of which he was secretary from 1906 until his death on October 2, 1934. The inscription on the tablet reads: "Erected in appreciation of a life devoted to the advancement of the profession of engineering and of his active part in obtaining from Andrew Carnegie the gift of the Engineering Societies Building."

The covering was removed by D. Robert Yarnall, president of United Engineering Trustees, who said, in part: "It is not necessary for the engineers of this generation to have a memorial in bronze or stone for Calvin Winsor Rice, because we knew him, and the memory of his human qualities, and his outstanding contribution to the advancement of our profession, whether mechanical, civil, mining, electrical, or chemical engineering, will last as long as we shall live; but it is fitting that future generations should have such a lasting memorial to perpetuate the memory of this outstanding engineering leader of our generation."

The tablet was prepared by the United Engineering Trustees, through a committee of which W. L. Batt, past-president of The American Society of Mechanical Engineers, was chairman. A rule of the trustees requires that memorials may not be placed in the public halls of the Engineering Societies Building until five years have elapsed since the death of those to be memorialized. Two years, therefore, remain before the tablet may be placed in the lobby of the building, and until that time it will remain in the custody of the ASME.

Doctor Rice was active in engineering-society work prior to accepting the secretaryship of the ASME in 1906, for he participated in the first co-operative project of the four great national engineering societies, namely, the establishment of the John Fritz Medal. In 1902, as chairman of the AIEE building committee, he made efforts to secure a building primarily to house the Lattimer Clark Library, the result of which was the gift by Andrew Carnegie of the Engineering Societies Building in New York. He served as a vice-president of the Institute from 1903 to 1905.

Future AIEE Meetings

North Eastern District Meeting
Lenox, Mass. (Pittsfield Section)
May 18–20, 1938

Summer Convention
Washington, D. C., June 20–24, 1938

Pacific Coast Convention
Portland, Ore., August 9–12, 1938

Southern District Meeting
Miami, Fla., November 1938

Gaston Planté Medal Awarded to G. W. Vinal

G. W. Vinal (M'19) has been chosen to receive the 1937 Gaston Planté Medal which is the initial award of this medal. Doctor Vinal is chief of the section of electrochemistry, National Bureau of Standards, Washington, D. C.; a biographical sketch is given in the "Personal Items" section of this issue.

Established in 1936 by the Société Française des Électriciens in memory of Gaston Planté, who contributed much to the early development of the storage battery, the medal is to be awarded triennially and will be accompanied by a sum in cash of 4,000 francs. It may be awarded to any person regardless of nationality, who makes an important contribution in the field of storage batteries, voltaic cells, or electrochemistry in general. The electrotechnical societies and committees of each country may propose a name to the commission of awards. Doctor Vinal was nominated by the AIEE for consideration for the medal in November 1936, and the medal was awarded to him at the December 20, 1937, meeting of the committee of award.

Columbia University Offers EE Scholarship

The governing bodies of Columbia University have placed at the disposal of the AIEE each year a scholarship in electrical engineering in the school of engineering of Columbia University for each class. The scholarship pays the annual tuition fees of $380. Reappointment of the student to the scholarship for the completion of his course is conditioned upon the maintenance of a good standing in his work.

To be eligible for the scholarship, the candidate recommended will have to meet the regular admission requirements, in regard to which full information will be sent without charge upon application to the secretary of the University or to the national secretary of the Institute.

In a letter addressed to the national secretary of the Institute, an applicant for this scholarship should set forth his qualifications (age, place of birth, education, reference to any other activities, such as athletics or working way through college, references, and photograph). A committee composed of W. I. Slichter, *chairman*, Francis Blossom, and H. C. Carpenter will con-

Future Meetings of Other Societies

American Institute of Mining and Metallurgical Engineers. Annual meeting, February 14–17, New York, N. Y.

Association of Iron and Steel Engineers. Annual spring conference, April 28–29, Baltimore, Md.

American Railway Engineering Association. March 15–17, Chicago, Ill.

American Society of Civil Engineers. Annual spring meeting, April 20–22, Jacksonville, Fla.

American Society of Mechanical Engineers. National spring meeting, March 23–25, Los Angeles, Calif.

American Society for Metals. Western Metal Congress, week of March 21, Los Angeles, Calif.

American Society for Testing Materials. 1938 regional meeting, March 7–11, Rochester, N. Y.

Edison Electric Institute. Engineering committees, May 2–5, Chicago, Ill.

National Electrical Manufacturers Association. Midwinter meeting, February 7–12, New York, N. Y.

National Fire Protection Association. May 9–13, Atlantic City, N. J.

The Society of Automotive Engineers. National passenger car meeting, March 28–30, Detroit, Mich.

sider the applications and will notify the authorities of Columbia University of their selection of a candidate. The last day for filing of applications for the year 1938–39 will be June 1, 1938.

The course at the Columbia school of engineering is a graduate course which may be either elective leading to the degree of master of science or prescribed leading to the degree of electrical engineer. For the former, requirement for admission is the completion of four-year course in electrical engineering as evidenced by a bachelor's degree from an approved institution. For the professional degree, the requirements are more specific as to course content and include a considerable proficiency in mathematics, physics, and chemistry, and some knowledge of the humanities, as well as the usual undergraduate technical courses. The candidate is admitted on the basis of his previous collegiate record without undergoing special examinations. Other qualifications being equal, members of the student branches of the AIEE will be given preference.

The purpose of this advanced course is to produce a high type of engineer, trained in the humanities as well as in the fundamentals of his profession. It is hoped that Enrolled Students and others qualified will show a keen interest in this scholarship.

Westinghouse Research Fellowships. The Westinghouse Electric and Manufacturing Company recently established an industrial fellowship at the Mellon Institute of Industrial Research of the University of Pittsburgh for the study of problems in dielectrics and electrical insulation. R. N. Wenzel, a member of the research staff of the Mellon Institute since 1927, has been appointed fellow in charge of this project. Doctor Wenzel is a graduate of the chemical-engineering department of Stanford University. The fellowship has as its general objective the development of improved insulating materials and processes, and brings the facilities of Mellon Institute into co-operation with those of the Westinghouse research laboratories. The Westinghouse company also has announced five post-doctorate fellowships for research in modern physics at the Westinghouse research laboratories in East Pittsburgh during 1938–39.

Code for Protection Against Lightning Issued

The National Bureau of Standards has issued a handbook comprising the first three parts of the "Code for Protection Against Lightning" which was prepared under the joint sponsorship of the Bureau and the AIEE, and approved by the American Standards Association. Part I of the code discusses the protection of persons, part II the protection of buildings and miscellaneous property, and part III the protection of structures containing inflammable liquids and gases. The origin, characteristics, and effects of lightning, and a bibliography are presented in appendixes. Parts IV and V are still under consideration and will be issued later.

M. G. Lloyd (A'08, F'12), chief, section of safety codes, National Bureau of Standards, is chairman of the committee that formulated the code. The AIEE is represented on this committee by W. W. Lewis (A'09, M'13), General Electric Company, Schenectady, N. Y.; Wills Maclachlan (A'08, F'21), Toronto, Can.; and A. M. Opsahl (A'26), Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.; several other Institute members serve on the committee as representatives of other groups. As National Bureau of Standards Handbook H21, the code is for sale by the Superintendent of Documents, Washington, D. C., at 15 cents per copy.

Welding Laboratory Planned. A gift of $20,000 has been made to Rensselaer Polytechnic Institute, Troy, N. Y., by George T. Horton, president of the Chicago Bridge and Iron Company. The gift will be used to establish a new welding laboratory.

American Engineering Council

Eighteenth Annual Meeting Held in Washington, D. C.

PROGRAMMED to "discuss current problems and arrive at conclusions representing the engineers' point of view and to reduce engineering opinion to resolutions designed to make engineers and their organizations more effective in the public interest and among themselves," the official representatives of 50 engineering organizations met January 13–15, 1938, in Washington, D. C., for the eighteenth annual assembly of American Engineering Council. The AIEE was represented by its official delegates: W. H. Harrison (part time), William McClellan, C. E. Stephens, and National Secretary H. H. Henline. Included on the program were meetings of Council's principal committees, election of officers, and the annual "All Engineers' Dinner."

The eighth conference of engineering-society secretaries, was held concurrently. This conference was devoted to discussion of problems concerning the effective management of engineering societies and the development of co-operation in society activities.

Officers Elected

William McClellan (A'04, F'12, past-president) AIEE representative on the AEC assembly, was elected president of Council for the ensuing two years. To serve as vice-presidents, A. J. Hammond, a representative of the American Society of Civil Engineers, and R. E. Flanders, a representative of the American Society of Mechanical Engineers, were re-elected for the two-year term 1938–39. L. J. Fletcher, representing the American Society of Agricultural Engineers, was elected treasurer for the year 1938. Vice-presidents who were elected for two-year terms last year and who therefore will serve the second half of their terms during 1939 are: J. S. Dodds, representative of the Iowa Engineering Society, and C. O. Bickelhaupt, representative of the AIEE.

Representatives and alternates to the assembly also were elected from the six geographical districts into which AEC membership organizations are divided. F. M. Feiker (M'34) was re-elected executive secretary.

The Executive Secretary Reports

In his annual report to the assembly, Executive Secretary F. M. Feiker summarized the actions of the executive committee and the work of the standing and special committees and staff of Council. He also outlined broadly the objectives of Council "as maintained against the background of the preceding year," and pre-

sented a "look ahead based on expectations of things to come."

Speaking of the relation of AEC to the public, Secretary Feiker said: "Public discussion of lobbying and propaganda makes it essential that AEC continue to clarify its position as a nonpartisan, fact-finding agency for the expression of engineering opinion on those public questions in which engineers may have a viewpoint in the public interest as citizens, as well as professional men. To those in public place, who are accustomed to being importuned by class groups for special class legislation, the organization and purpose of the AEC as an agency to which they may come with assurance of securing factual information, is difficult to believe. From those, on the other hand, who have sought and secured this type of counsel during the past four years, comes appreciation. Of course, by some in public place, the "lobby tag" will be pinned on any organization which expresses a point of view for public guidance, or upon any individual who acts for such an organization, but every effort has been made by the officers and by the staff to emphasize the fact that actions of AEC are not founded in self-seeking but in the public interest."

Speaking of changes in national policy, Mr. Feiker pointed out that "the work of Council not only for the last year, but for the last four years, has been carried out in an atmosphere of legislative and administrative action, distinctive in the history of the federal government of the United States. A program of social and economic legislation framed by the administration under national emergency conditions has related engineers both individually and collectively to the public welfare in new ways. . . . Government agencies have called upon AEC for help in many different directions. Council's opportunities have been those of keeping up with a complex and changing governmental structure and maintaining itself as an agency of service rather than as an agency of debate on policy. . . ."

Mr. Feiker reported that during the last six months of 1937 there had been an increase in the number of requests from congressional committees and individual congressmen seeking advice from AEC on legislative proposals, and an increase in the number of requests to furnish information of factual character in public affairs.

Discussing the day-to-day activities of Council and of the staff, Mr. Feiker said: "An honest effort is made to do that which seems most likely to result in the greatest good for the largest number of engineers or to prove most effective in the public welfare. Frequently, contacts are made in confidence and results depend, in part at least, upon keeping those confidences. Many of those who use the engineering knowledge and experience made available to them by the engineering profession through Council's employees would not continue to do so unless they felt free to discuss their problems 'off the record' and were certain that no publicity would be connected with their inquiries. . . . It [Council] serves as a clearing house for questions of a public nature which require technological knowledge and engineering experience, and acts as an advisory body, in connection with problems of government, for its engineering member societies. It is also an agency of inquiry into economic and social problems as they may be affected by technology, and more particularly by engineering.

"With the change in Federal Government administration and the expansion of its work and organization has come the need for speed and a somewhat different technique in the engineering approach to problems in public affairs and to government officials and employees functioning under the newly centralized system. This was especially true with the enormous emergency agencies. Instead of the normal process of handling engineering matters in public affairs and of analyzing and dealing with legislation, AEC has had to work for several years with emergency government agencies whose authority and funds have been more frequently established and provided by executive orders than by Congress. Council's work has, therefore, had to be changed from the more systematic process of committee reports, hearings, and procedures to the very specific act of keeping up with rapidly changing conditions, and relating engineering knowledge and experience directly to even more temporary than permanent situations. . . .

"Contacts are maintained with scores of individuals in more than 70 government agencies, with members and committees of the House and Senate, and with many other organizations interested in public affairs or likely to be concerned with problems on which engineering opinion might be helpful and effective. In many instances, there are basic differences of opinion and philosophy which have to be tactfully respected in all that is done to have such contacts accept the factual information they get from the American Engineering Council without question. The staff is happy to report that its relations with every contact are pleasant and that there is an increasing demand from government agencies for advice and assistance."

The remainder of Mr. Feiker's report primarily summarized the activities of AEC during the year 1937, many of which have been reported from month to month in ELECTRICAL ENGINEERING.

"In facing its future responsibilities," Mr. Feiker concluded: "Council should be cognizant of some trends and tendencies that have a bearing on its work. Among others, these include the growing concern on the part of young engineers as to the future of their profession and their part in it, the increasing complexity of our technology and its economic and social impacts, and the consequent result that government's relationship to technology and industry is changing.

"These point to three parallel paths of action for Council:

First, a program looking to a better understanding of the individual's relation to his profession and its return to him. The earning and educational study is the first step in this. Others should follow.

Second, a program of analysis of the impact of technology on society. Specifically, a study and report on work-creating technology seems badly needed.

Third, continuing the present program of making available for public guidance the facts and experience of the members of the profession.

"A basic element in all these programs is mutual confidence and understanding among the leaders in the various branches of the profession—a confidence that can come only when the leaders know each other on an intimate basis. Leaders change from year to year, viewpoints change, personalities change, and with these changes come corresponding shifts in the viewpoint of the profession. Council has a definite responsibility to bring these viewpoints and personalities together. Success as an agency of the profession depends almost entirely on the unity of its approach.

"The measure of success which Council has achieved, the quality of leadership of its founders and of those who have continued to advance its purposes, give us confidence that within the AEC organization there is the capacity to meet the challenge of the changing times."

Student Branch at Case School of Applied Science

ENROLLMENT of 100 per cent of its junior and senior electrical-engineering students has been the admirable record of the AIEE Student Branch at Case School of Applied Science, Cleveland, Ohio, which is said to be one of the most active organizations on the Case campus. The accompanying illustration shows this year's members. Present officers are: S. H. Hanville, *chairman;* H. P. Knox, *vice-chairman;* R. A. Engelhardt, *secretary-treasurer;* J. E. Duff, *safety director;* Professor A. C. Seletzky, *counselor.*

Letters to the Editor

CONTRIBUTIONS to these columns are invited from Institute members and subscribers. They should be concise and may deal with technical papers, articles published in previous issues, or other subjects of some general interest and professional importance. ELECTRICAL ENGINEERING will endeavor to publish as many letters as possible, but of necessity reserves the right to publish them in whole or in part, or reject them entirely.

ALL letters submitted for consideration should be the original typewritten copy, double spaced. Any illustrations submitted should be in duplicate, one copy to be an inked drawing but without lettering, and other to be lettered. Captions should be furnished for all illustrations.

STATEMENTS in these letters are expressly understood to be made by the writers; publication here in no wise constitutes endorsement or recognition by the American Institute of Electrical Engineers.

Interest in Section Meetings

To the Editor:

At the December meeting of the AIEE North Carolina Section at Duke University in Durham, N. C., there was a registered attendance of 120, of which 76 came from outside of Durham. These 76 men traveled 6,400 miles to get to the meeting and 6,400 miles on the return trip, or an average of 168 miles per man.

An expenditure of 12,800 man-miles to attend a Section meeting speaks well for the interest in our Section.

Yours very truly,
W. J. SEELEY (A'19, M'28)

Past Chairman, AIEE North Carolina Section; Professor and Head of Department of Electrical Engineering, Duke University, Durham, N. C.

Graphical Solution of Multiple Resistance and Reactance

To the Editor:

A direct graphical method of determining the equivalent impedance of a resistance and reactance in multiple, such as illustrated in figure 1, is shown in figure 2.

The resistance is laid off horizontally to any desired scale. The reactance is laid off vertically at the tip of the resistance vector, upward if inductive reactance and downward if capacitive reactance. Join the heel of the resistance vector to the toe of the reactance as with dotted line OB. Line OB is their vector sum and incidentally their *series* impedance. Then with O as center and the length, OA, of the resistance vector as radius, describe an arc cutting the diagonal OB at point C. Vertical line CD will then represent the numerical value of the equivalent impedance of the multiple combination.

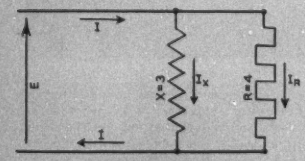


Figure 1

The component parts, resistance, r, and reactance, x, of this impedance, Z, may be determined by drawing a line from D and perpendicular to OB. Figure 2 indicates the relative values. It may be noted that the characteristic angle, θ, of impedance, Z, will be angle ABO = DCO, which is the angle whose tangent is R/X. This, incidently is the complement of angle BOA, where BOA is the characteristic angle of a series combination of R and X. The tangent of angle BOA is X/R.

In figure 3 is shown a second method of finding Z. In this case X is taken as a radius with center at B, the arc cutting diagonal OB at point E. Then EF, drawn perpendicular to AB, is the numerical value

Figure 2

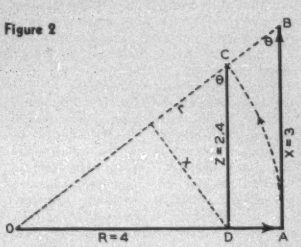
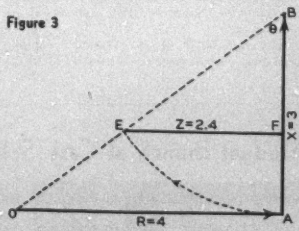


Figure 3



of Z, to the same scale as R and X, and its characteristic angle is θ the same as before. Tan $\theta = R/X$.

Figure 4 shows a different method, similar to that previously used in finding the equivalent impedance of similar impedances in multiple (EE, October 1937, page 1327). To any chosen base line perpendiculars are erected at any desired distance apart, S, and of lengths to any desired common scale equal to R^2 and X^2. From the intersection of the cross diagonals a third perpendicular is drawn to the base line. Its length represents the numerical value of Z^2. Extracting the square root of this will give Z. The characteristic angle of Z does not appear on the diagram in this case. It will of course be θ, where tan $\theta = R/X$.

Figure 4

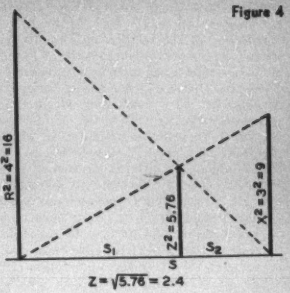


Figure 5

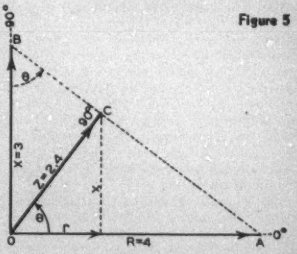


Figure 5 shows what seems to be the simplest of the solutions for the equivalent impedance of a resistance and a reactance in multiple. Lay off horizontal distance OA equal to the resistance, R. Lay off vertical distance OB equal to the reactance, X. Draw line AB. From common point O draw line OC perpendicular to AB. Length OC is the equivalent impedance, Z, of the multiple combination and lies in the diagram at its correct characteristic angle, $\theta = \tan^{-1} x/r = \tan^{-1} R/X$.

It may be noted that in the preceding discussion inductive reactance has been assumed. If capacitive reactance were to replace the inductive reactance, AB in figures 2 and 3, and OB in figure 5, it would be measured downward. In other respects the same procedure would be followed as with inductive reactance. If capacitive and inductive reactance were both in multiple with pure resistance, one would subtract from the other in the usual manner, the difference taking the course of the larger, upward if inductive or downward if capacitive reactance.

APPENDIX

In figure 1,

$I^2 = I_R^2 + I_X^2$ or $(E/Z)^2 = (E/R)^2 + (E/X)^2$

$1/Z^2 = 1/R^2 + 1/X^2$ or

$$Z^2 = \frac{R^2X^2}{(R^2 + X^2)} \text{ or } Z = \frac{RX}{\sqrt{R^2 + X^2}}$$

In figure 2,

$CD/AB = OC/OB$, but $AB = X$; $OC = R$; and $OB = \sqrt{R^2 + X^2}$

Therefore $CD/X = R/\sqrt{R^2 + X^2}$ or

$CD = RX/\sqrt{R^2 + X^2} = Z$

Therefore $CD = Z$

The characteristic angle of Z may be

determined by the application of a simple theorem in the algebra of complex quantities: "The product of two points is defined as *the point whose angle is the sum of the angles of the given points* and whose distance is the product of the distances; the quotient of two points is a *point whose angle is the angle of the dividend minus the angle of the divisor* and whose distance is the quotient of the distances of the two points."

With the angle of R equal to 0 degrees; the angle of X equal to 90 degrees; and the angle of $\sqrt{R^2 + X^2}$ equal to the angle whose tangent is X/R; it follows that the angle of RX will be 0 + 90 or 90 degrees. Also it follows that $RX/\sqrt{R^2 + X^2}$ will have an angle of $0 + 90 - \tan^{-1}(X/R)$ and this is $\tan^{-1}(R/X)$.

In figure 3,

$EF/OA = BE/BO$, but $BE = BA = X$; $OA = R$; and $BO = \sqrt{R^2 + X^2}$

Therefore $EF/R = X/\sqrt{R^2 + X^2}$ or $EF = RX/\sqrt{R^2 + X^2} = Z$

Therefore $EF = Z$

In figure 4,

$S_1 = SZ^2/X^2$ and $S_2 = SZ^2/R^2$. But $S = S_1 + S_2$

Therefore $S = SZ^2(1/X^2 + 1/R^2)$ or $1/Z^2 = 1/X^2 + 1/R^2$

Therefore $Z^2 = R^2X^2/(R^2 + X^2)$ or $Z = RX/\sqrt{R^2 + X^2}$

In figure 5,

$OC/OB = OA/AB$. Therefore $OC = OA \times OB/AB$

Therefore $OC = RX/\sqrt{R^2 + X^2} = Z$

Very truly yours,

E. C. GOODALE (A'27)

Inspector, Puget Sound Power and Light Company, Olympia, Wash.

Tensor Analysis

To the Editor:

In his very interesting paper, "What Is Tensor Analysis?" (*EE, January 1938, pages 5–9*) Doctor Banesh Hoffmann makes the "parallelogram law of addition" the fundamental property which distinguishes vectors from other objects describable in terms of components. This seems to suggest that before the question can be answered as to whether a given group of objects is describable as a group of vectors, some law of addition for these objects must be *defined*, and that this law must have the "parallelogram" property. It also suggests that a single object cannot be regarded as a vector, since a "law of addition" clearly can have no meaning for a single object.

Doctor Hoffman seems to imply (page 5) that the equations of transformation of the components of a contravariant vector (1.16) may be derived from the "parallelogram law of addition." However, Doctor Hoffmann will certainly admit that covariant vectors also have a "parallelogram law of addition" and that these vectors do not satisfy equation 1.16. There seems to be here a serious *non sequitur*.

It is possible to go even farther, and exhibit "objects" which have a "parallelogram law of addition" and whose components satisfy neither equation 1.16 nor the more general equation 1.14 and are therefore neither vectors nor tensors. Let $u(x_1x_2)$, $v(x_1, x_2)$ . . . . .etc., be twice differentiable functions of the co-ordinates x_1x_2 of a point in a plane. Consider the two second derivatives of any one of these functions with respect to each of the co-ordinates $\left(\frac{\partial^2 u}{\partial x_1^2}, \frac{\partial^2 u}{\partial x_2^2}\right)$ at some particular point on the plane. Regard these two second derivatives as the components of an "object," attached to the function u. Now a very reasonable definition of a law of addition for these "objects" would be that the "object" attached to u, added to the "object" attached to v, gives the "object" attached to $(u + v)$, that is the object with components $\left(\frac{\partial^2(u+v)}{\partial x_1^2}; \frac{\partial^2(u+v)}{\partial x_2^2}\right)$. But since

$$\frac{\partial^2(u+v)}{\partial x_1^2} = \frac{\partial^2 u}{\partial x_1^2} + \frac{\partial^2 v}{\partial x_1^2}$$

$$\frac{\partial^2(u+v)}{\partial x_2^2} = \frac{\partial^2 u}{\partial x_2^2} + \frac{\partial^2 v}{\partial x_2^2}$$

this is a "parallelogram law of addition." These relations hold irrespective of what co-ordinate system is used to designate the points of the plane.

Thus we have here, objects whose components are defined with respect to any co-ordinate system, and a law of addition which is defined for any co-ordinate system, and such that the "parallelogram law of addition" holds for any co-ordinate system. Nevertheless, as calculation will show, the components of these "objects" satisfy neither the equations 1.16 nor 1.14 and are not the components of a vector or a tensor.

Authorities such as Levi-Civita and Weyl make the equations 1.14 and 1.16 fundamental as defining tensors and contravariant vectors. From these equations it follows that we may define a "parallelogram law of addition." However, the converse is not true. From a "parallelogram law of addition" alone we cannot derive equations 1.14 and 1.16. The "parallelogram law of addition" is not the feature which distinguishes vectors from other "objects."

Very truly yours,

J. SLEPIAN (A'17, F'27)

Consulting Research Engineer, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.

Personal Items

F. B. JEWETT (A'03, F'12, Edison Medalist '28, past-president) vice-president of the American Telephone and Telegraph Company and president of the Bell Telephone Laboratories, Inc., New York, N. Y., has been elected to receive the Washington Award for 1937. Details of the award are given on pages 78–9, in this issue. Doctor Jewett was born at Pasadena, Calif., September 5, 1879, and in 1898 was graduated from Throop Polytechnic Institute (now California Institute of Technology) with the degree of bachelor of arts. He then enrolled in the graduate school of the University of Chicago, receiving the degree of bachelor of philosophy in 1902. After serving for one year as an assistant at the University of Chicago, he became an instructor in physics and electrical engineering at Massachusetts Institute of Technology, and in 1904 he joined the staff of the American Telephone and Telegraph Company. In 1912 he became assistant chief engineer of the Western Electric Company, in 1916 chief engineer, and in 1921 vice-president of the company. At the beginning of 1925 he became vice-president of the American Telephone and Telegraph Company, and at the same time was made president of the Bell Telephone Laboratories, Inc., which positions he has since held. Doctor Jewett has served the Institute as manager, 1915–18; vice-president, 1918–19; and president 1922–23. He has served also on many of the Institute's committees and as its representative on several other bodies. He has presented many papers before the Institute and other societies, and has been active in the Engineering Foundation and National Research Council. Since the formation of the Institute's committee for the Iwadare Foundation in 1931, Doctor Jewett has been its chairman. In 1928 Doctor Jewett was awarded the Edison Medal of the AIEE. Among other honors, the Japanese government has bestowed upon him the Fourth Order of the Rising Sun and the Third Order of the Sacred Treasure.

F. B. JEWETT

WILLIAM MCCLELLAN (A'04, F'12, past-president) president of the Potomac Electric Power Company, Washington, D. C., recently was elected president of the American Engineering Council for the two-year period 1938–39. Doctor McClellan was born November 5, 1872, at Philadelphia, Pa., and was graduated from the University of Pennsylvania with the degree of bachelor

S. B. WILLIAMS

C. F. HIRSHFELD

HARADEN PRATT

of science in 1900; in 1903 he received the degree of doctor of philosophy. He was instructor in electricity and magnetism in the department of physics at that university from 1900 until 1905. Several years later he returned to the University of Pennsylvania as dean of the Wharton School of Finance and Commerce, and in later years continued his association with the university as director general of the alumni association and as a trustee. From 1900 until 1904 Doctor McClellan worked in various capacities for the Union Traction and Philadelphia Rapid Transit Company besides his regular teaching duties. In 1905 he went to New York, N. Y., to do design work for Westinghouse, Church, Kerr, and Company on the lighting and power distribution for the Pennsylvania Railroad terminal. From 1907 until 1915 Doctor McClellan was vice-president of the Campion-McClellan Company, and in the latter year became a member of the firm of Paine, McClellan, and Campion. During the period of 1919–21 he was vice-president of the Cleveland Electrical Illuminating Company. In 1922 he became a member of the firm of McClellan and Junkersfeld, remaining in that firm until he was elected vice-president of the Stone and Webster Engineering Corporation in 1929. At present he is president of William McClellan and Company, Ltd. Doctor McClellan has served the Institute as manager, 1912–15; vice-president, 1915–17; president 1921–22; and as member or chairman of many of the technical and general committees.

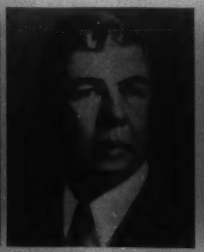
HARADEN PRATT (A'15, F'37) vice-president and chief engineer of the Mackay Radio and Telegraph Company, New York, N. Y., has been elected president of the Institute of Radio Engineers for the year 1938. Mr. Pratt was born at San Francisco, Calif., July 18, 1891, and received the degree of bachelor of science at the University of California in 1914. Following his graduation he became an assistant engineer during the construction and preliminary operation of the Marconi transoceanic radio stations at Bolinas and Marshall, Calif. From 1915 until 1920 Mr. Pratt was expert radio aide in the Bureau of Steam Engineering of the United States Navy Department, at Mare Island, Calif., and at Washington, D. C. In 1920 he became engineer of the Federal Telegraph Company, Palo Alto, Calif., where he remained for two years before becoming engaged in the development of radio aids for air navigation, in collaboration with the United States Department of Commerce and some commercial airlines. Mr. Pratt became vice-president and chief engineer of the Mackay Radio and Telephone Company in 1928. He has been identified with radio engineering standardization work since 1929, and in 1935 was chairman of the standards committee of the Institute of Radio Engineers. He has been active in committee work of the American Standards Association, and served as technical advisor for the United States Government at the International Radio Telegraph Conference held at Washington, D. C., in 1927. He served also as technical advisor of the United States delegation to the conference of the International Technical Consulting Committee on Radio Communication held at Copenhagen in 1931. Mr. Pratt is a member of the Radio Corporation of America, Institute of Aeronautical Sciences, and Sigma Xi.

C. F. HIRSHFELD (A'05, F'36) chief of the research department of The Detroit Edison Company, Detroit, Mich., recently received the Worcester Reed Warner Medal of The American Society of Mechanical Engineers "for his research and contributions to the theory and practice of heat-power engineering." Doctor Hirshfeld was born January 30, 1881, at San Francisco, Calif., and received the degree of bachelor of science in electrical engineering at the University of California in 1902. He received the degrees of master of mechanical engineering (1905) and doctor of engineering (1932) at Cornell University and Rensselaer Polytechnic Institute, respectively. Following his graduation from the University of California he became an instructor at Cornell University in 1903, later becoming assistant professor and professor of mechanical engineering, remaining there until 1914, when he was appointed chief of research of The Detroit Edison Company. Doctor Hirshfeld was chairman of the Engineers' Council for Professional Development from its beginning until 1935, and formerly was active as a member of the division of industrial and engineering research of the National Research Council. Doctor Hirshfeld is the author of several books and many papers and articles on technical subjects. He has served as a member of the Institute's committees on power generation, standards, and electrical machinery. He is a member of the American Society for Testing Materials, American Institute of Mining and Metallurgical Engineers, American Association for the Advancement of Science, Sigma Xi, and Tau Beta Pi.

S. B. WILLIAMS (M'37) since 1936 managing editor of *Electrical World*, New York, N. Y., has been appointed editor of that publication. Mr. Williams was born August 2, 1889, at Orinoke, Kans., and received the degrees of bachelor of literature (1912) and electrical engineer (1914) at Princeton University, following which he joined the editorial staff of *Electrical World* and eventually became assistant managing editor. In 1922 he became associated with the Gage Publishing Company, New York, N. Y., as managing editor, and later editor, of *Electrical Record*. Mr. Williams was editor and manager of *The Electragist* from 1924 until 1928, when he returned to the McGraw-Hill Publishing Company as editor of *Electrical Contracting*. He held that position for eight years before being transferred to the editorial staff of *Electrical World*. Mr. Williams is a member of the Illuminating Engineering Society.

F. W. GARDINER (A'07) formerly principal assistant engineer of the Interborough Rapid Transit Company, New York, N. Y., recently was appointed chief engineer of that company. Mr. Gardiner was born in New York, November 30, 1870, and was graduated from Stevens Institute of Technology with the degree of mechanical engineer in 1892. For seven years prior to his affiliation with the Interborough Rapid

WILLIAM McCLELLAN



L. A. HAZELTINE

F. W. GARDINER

H. H. PORTER

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G. W. VINAL

F. O. McMILLAN

Transit Company he was engaged in construction and inspection work for the New York Central Railroad Company. He has been principal assistant engineer of the Interborough Company since 1903, and has been a member of the company's engineering staff since 1899. Mr. Gardiner is a member of the American Society of Civil Engineers, American Railway Engineering Association, and American Transit Association.

L. A. HAZELTINE (F'35) professor of electrical engineering, Stevens Institute of Technology, Hoboken, N. J., recently was awarded the first Armstrong Medal of the Radio Club of America. Professor Hazeltine was born August 7, 1886, at Morristown, N. J., and received the degree of mechanical engineer at Stevens Institute of Technology in 1906, following which he entered the test department of the General Electric Company, Schenectady, N. Y., returning to his alma mater in the following year to become an assistant in electrical engineering. He received successive appointments as instructor, assistant professor, and acting professor, becoming professor and head of the department of electrical engineering in 1918. Professor Hazeltine has served as consulting engineer to the United States Navy and to several commercial organizations. He is the author of many papers and articles on radio communication and electronic applications, and is generally credited with having introduced some basic concepts of communication circuits. He is a member of the Institute of Radio Engineers.

H. H. PORTER (A'96, M'12, Life Member) president of the American Water Works and Electric Company, Inc., and member of the consulting engineering firm of Sanderson and Porter, New York, N. Y., has become chairman of the board of directors of the American Water Works and Electric Company. Mr. Porter was born March 12, 1865, at New York, N. Y., and was graduated from Columbia University in 1886. Recently he was elected a life trustee of that institution. In 1891, following five years of graduate study and preliminary engineering training he became engineer and salesman with the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., where he remained until the firm of Sanderson and Porter was formed in 1896. Mr. Porter is a director of several electric utility companies. From 1929 until 1933 he was chairman of Engineering Foundation and was a member of the board of trustees of the United Engineering Trustees, Inc., from 1927 until 1932. During 1916–17 he was a member of the Institute's committee on public policy (now Institute policy). Mr. Porter is a member of the American Society of Civil Engineers, American Institute of Mining and Metallurgical Engineers and The American Society of Mechanical Engineers.

G. W. VINAL (M'19) physicist and chief of the section of electrochemistry, National Bureau of Standards, Washington, D. C., has been awarded the Gaston Planté Medal of the Société Française des Electriciens. The medal is "awarded every three years and accompanied by a sum in cash of 4,000 francs . . . . to any person, whether from France or any other country, who, by his work of a scientific or technical nature will bring an important contribution to the industry of electric storage batteries, photovoltaic cells, or electrochemistry in general." Born at Ellington, Conn., December 17, 1882, Doctor Vinal received the degree of bachelor of arts in 1906 from Wesleyan University, studied in the graduate school at The Johns Hopkins University during 1906–07 and at Wesleyan University in 1907–08, receiving from Wesleyan the degrees of bachelor of arts in 1909 and bachelor of science in 1936. Since 1908 Doctor Vinal has been a member of the staff of the National Bureau of Standards at Washington, and in 1918 became chief of the Bureau's section of electrochemistry, dealing principally with electrical batteries, including standard cells, dry cells, and storage batteries. Doctor Vinal is the author of numerous books and papers on electrochemical subjects, many of which have been translated into other languages. He is a member of the American Physical Society.

F. O. McMILLAN (A'14, F'32, past vice-president) since 1920 research professor of electrical engineering, Oregon State College, Corvallis, has been appointed head of the electrical engineering department of that Institution. Professor McMillan was born at Albia, Iowa, May 12, 1890, and received the degree of bachelor of science in electrical engineering at Oregon State College in 1912; in 1919 he received the degree of master of science in electrical engineering at Union College. Following his graduation in 1912 he became a student engineer in the testing department of the General Electric Company, Schenectady, N. Y., and in the following year was transferred to the railway engineering department of that company. He became assistant professor of electrical engineering at Oregon State College in 1920, and three years later was appointed associate professor. In addition to his regular teaching duties, Professor McMillan has served as consulting electrical engineer for the State of Oregon, the United States Bureau of Fisheries, the North West Electric Light and Power Association, and several organizations. Professor McMillan served as a vice-president of the Institute from 1934 until 1936. He is a member of the current committee on transfers and previously has served as a member of the committees on student branches, basic sciences (electrophysics) and research. He is a member of the Northwest Electric Light and Power Association, Sigma Xi, Tau Beta Pi, and several other societies.

R. A. MCCARTY (A'16, M'32) manager of the generator division, Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., recently was appointed manager of the small motor division of that company, with offices at Lima, Ohio. Mr. McCarty, a native (1882) of Mooresburg, Tenn., was graduated from the University of Tennessee, 1903, following which he entered the test course of the Westinghouse company. He entered the power engineering division in 1906, and three years later was assigned to motor engineering. In 1910 he was made engineer in charge of insulation design and became section engineer a year later in the power-engineering department. In 1928 Mr. McCarty was appointed division engineer, and two years later became manager of the power-engineering department. He became manager of the generator division in 1935.

C. H. WILLIS (A'22, M'28) associate professor of electrical engineering at Princeton University, has been appointed Arthur le Grand Doty professor of electrical engineering. Doctor Willis was born August 5, 1927, in Culpeper County, Va., and was graduated from the University of Richmond in 1914 with the degree of bachelor of science. He then enrolled in The Johns Hopkins University and received the degrees of bachelor of science in engineering (1916) and doctor of philosophy (1926). After his graduation in 1916 he returned to the University of Richmond as instructor in physics, and eventually became professor of applied physics at that institution. He was appointed to the electrical engineering faculty of Princeton University in 1926, becoming associate professor in 1929.

K. A. PAULY (A'03, M'12) engineer in the industrial department of the General Electric Company, Schenectady, N. Y., has retired after a total of 39 years of service, but will remain in a consulting capacity.

A native (1872) of Springfield, Mass., Mr. Pauly was graduated from the Massachusetts Institute of Technology in 1896. He entered the General Electric test course in 1899, and in 1901 was transferred to the induction-motor department, working there as a designer until 1905, when he was transferred to the power and mining department.

In 1922 Mr. Pauly was made engineer of the power and mining department, and when this department was renamed the industrial engineering department, he continued in the position of engineer.

C. W. WILDER (A'06, F'14) electrical engineer for the Consolidated Edison Company of New York, Inc., New York, N. Y., and its predecessor company, The New York Edison Company, since 1919, has retired from active service. A graduate of Massachusetts Institute of Technology in the class of 1896, Mr. Wilder engaged in general engineering work on lighting, industrial, and railroad properties in Boston, Mass., and New York, until 1907, when he joined the staff of the Public Service Commission for the first district of New York. He resigned from the Commission to join The New York Edison Company.

R. R. WHIPPLE (A'30, M'36) assistant professor of electrical engineering at the University of Iowa, Iowa City, has been appointed designing illuminating engineer for the Trippe Manufacturing Comany, Chicago, Ill. Professor Whipple has been a member of the faculty of the electrical engineering department at the University of Iowa since 1928. He is the author of several papers on illuminating engineering subjects and is a member of the Illuminating Engineering Society.

C. F. SCOTT (A'92, F'25, HM'29, Edison medalist '29, past-president, member for life) professor of electrical engineering emeritus, Yale University, New Haven, Conn., has been elected vice-president of the National Council of State Boards of Engineering Examiners for the year 1938.

C. H. JOHNSON (M'35) who has been electrical engineer for the Idaho Maryland Mines Corporation, Grass Valley, Calif., has been appointed electrical engineer for the General Electric Company, San Francisco.

C. E. GREENE (M'31) for the past ten years electrical and mechanical engineer for Metcalf and Eddy, Boston, Mass., has been appointed to a similar position with the consulting firm of Cleverdon, Varney, and Pike, with offices in Boston.

Obituary

NORMAN TRYON WILCOX (A'95, M'96, F'12, member for life) consulting engineer, Wolfeboro, N. H., died December 31, 1937. Mr. Wilcox was born October 24, 1862, at Meriden, Conn., and began his technical career with the Meriden Britannia Company in 1882. In the following year he went to Montana to establish his own company, but four years later returned to Lynn, Mass., to take the "expert" course of the Thomson-Houston Electric Company, where he remained until 1895. In that year Mr. Wilcox became manager of the Seneca Electric Company, Seneca Falls, N. Y., remaining with that company until 1897, when he became superintendent of the Chattanooga Electric Light and Power Company, Chattanooga, Tenn. In 1900 he became general superintendent of the Colorado Electric Light and Power Company, but two years later became affiliated with Stone and Webster, Boston, Mass., as manager of central station properties. He remained with that organization until a few years ago, when he retired from active service and was retained as consulting engineer for the Public Service Commission of New Hampshire. During the World War Mr. Wilcox served as a member of the Naval Consulting Board of the United States.

WILBUR STANLEY WERNER (A'24) president of the Kelley-Koett Manufacturing Company, Inc., Covington, Ky., died December 16, 1937. Mr. Werner was born at Covington, July 19, 1895, and was employed by the Kelley-Koett Manufacturing Company in 1917. Except for a brief period of service with the United States Army during 1918–19, Mr. Werner's service with the Kelley-Koett Manufacturing Company was continuous for more than 20 years. During that time he served in various executive positions in the company and later became president. In 1929 he was chosen by the president of the United States to serve on a committee, known as the National Advisory Committee for X-Ray and Radium Protection, to act in an advisory capacity in preparing specifications for X-ray and radium protection. Mr. Werner was a member of the American Society of Radiology and the International Congress of Radiology.

HARRY G. COTTER (A'35) electrical engineer for the Great Lakes Towing Company, Toledo, Ohio, died in 1937 according to word just received at Institute headquarters. Mr. Cotter was born March 24, 1911, at Toledo. He was graduated from the University of Michigan with the degree of bachelor of science in engineering in 1933; he then enrolled in the graduate school of electrical engineering at that institution and received the degree of master of science in engineering in 1934. Following his graduation he was employed by the Great Lakes Towing Company, and was placed in charge of all electrical work for the company.

EMIL ERNEST KELLER (A'93, member for life) president of the Standard Screw Products Company, Detroit, Mich., died January 8, 1938. Mr. Keller was born in New York, N. Y., and attended the German-American Institute at Rochester, N. Y., before becoming a machinist's apprentice in the firm of Yawman and Erbe, of Rochester, N. Y. In 1886 he joined the Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa., and during the Columbian Exposition in Chicago, in 1893, was general manager of the fair's electric lighting system. He served also as vice-president and general manager of the Westinghouse Machine Company before organizing the Detroit Insulated Wire Company in 1906. Before becoming president of the Standard Screw Products Company in 1914, Mr. Keller was associated with the Insulating Materials Company and Metal Products Company. He was also a director of the Detroit Motorbus Company and the Michigan Terminal Warehouse Corporation.

JOHN PEARSON (A'02) superintendent of power plant, St. Croix Power Company, Somerset, Wis., died in April 1937, according to word just received at Institute headquarters. Mr. Pearson was born June 5, 1872, near Lund, Sweden, and received his technical education through the International Correspondence Schools. In 1896 he was employed by the Minneapolis Street Railway Company; in 1900 he became substation operator of the St. Paul Gas Light Company; and in 1901 became power plant superintendent for the St. Croix Power Company.

GEORGE EDWARD MCLEAN (A'27) superintendent of the British Columbia Electric Railway Company, Ltd., Ruskin, B. C., Canada, died October 16, 1937. Mr. McLean was born at Pittsburgh, Ont., Canada, March 16, 1880. He spent his entire technical career in the services of the British Columbia Electric Railway Company, starting as a substation mechanic in 1914. In 1923 he was made master mechanic of construction at Stave Falls, B. C., and later was transferred to Ruskin as the company's superintendent.

BENNET CARROLL SHIPMAN (M'31) research engineer, Servel, Inc., Evansville, Ind., died November 17, 1937. Mr. Shipman was born October 16, 1871, near Lewinsville, Va., and was graduated from Georgetown University with the degree of bachelor of arts in 1892. In 1908 he became senior member of the firm of Shipman, Denny, and Rhame, and much of his career was spent in consulting engineering until 1936, when he became research engineer for Servel, Inc.

Membership

Recommended for Transfer

The board of examiners, at its meeting on January 13, 1938, recommended the following members for transfer to the grade of membership indicated. Any objections to these transfers should be filed at once with the national secretary.

To Grade of Member

Anderson, A. S., assistant superintendent of distribution, New Orleans Public Service, Inc., New Orleans, La.

Boruch, E. R., vice-president, Standard Electric Manufacturing Company, Dallas, Texas.
Curran, C. L., consulting engineer, Broadus, Mont.
Jobe, C. L., power system planning engineering, Oklahoma Gas and Electric Company, Oklahoma City.
Lewis, Dixon, electrical conductor sales engineer, Aluminum Company of America, Detroit, Mich.
Lidsky, Louis, Sr. partner, L. and P. Electric Company, Brooklyn, N. Y.
Ramsay, J. W., associate professor of electrical engineering, University of Texas, Austin.
Zimmer, A. R., associate professor of electrical engineering, University of Toronto, Toronto, Ont., Canada.

8 to Grade of Member

Applications for Election

Applications have been received at headquarters from the following candidates for election to membership in the Institute. If the applicant has applied for direct admission to a grade higher than Associate, the grade follows immediately after the name. Any member objecting to the election of any of these candidates should so inform the national secretary before February 28, 1938, or April 30, 1938, if the applicant resides outside of the United States or Canada.

Anderson, J. S., Gilfillan Brothers, Inc., Los Angeles, Calif.
Andrews, E., Callite Products Corporation, Union City, N. J.
Ardahl, E. H., Emerson Electric Manufacturing Company, St. Louis, Mo.
Auer, W. L., Tennessee Valley Authority, Chattanooga, Tenn.
Barnes, C. B., Standard Oil Company of California, La Habra, Calif.
Barry, J. G., University of Pennsylvania, Philadelphia, Pa.
Bauer, W. C., Southern Bell Telephone and Telegraph Company, Jackson, Mississippi.
Baumbach, E. J., Public Service Company of Northern Illinois, Chicago, Ill.
Becklund, O. A., General Electric Company, Schenectady, N. Y.
Bills, G. W., University of Washington, Seattle, Wash.
Brownell, G. R. (Member) Consolidated Edison Company of New York, Inc., New York, N. Y.
Buehman, A. H., General Electric Company, Schenectady, N. Y.
Buffington, R. B., General Electric Company, Schenectady, N. Y.
Cady, D. P., Maydwell and Hartzell, Inc., Los Angeles, Calif.
Caldwell, J. F., Georgia Power Company, Columbus, Ga.
Campbell, H. C., Pennsylvania Railroad, Altoona, Pa.
Chelton, H. C., 12 West Madison Street, Baltimore, Md.
Christensen, P. M., Colt's Patent Fire Arms Manufacturing Company, Hartford, Conn.
Clair, S., I.R.T. Company, Bronx, N. Y.
Clear, F. L., Public Service Company of Oklahoma, Tulsa.
Cleaveland, G. W., Public Service Company of Colorado, Denver.
Constantinou, C., New York State Employment Service, New York, N. Y.
Cook, J. E., (Member) Brooklyn Edison Company, Inc., Brooklyn, N. Y.
Cooper, J., Placer Development Syndicate, Vancouver, B. C., Canada.
Coster, R. A., Brooklyn Edison Company, Brooklyn, N. Y.
Covington, W. S., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Cox, J. L., Georgia Power Company, Athens, Ga.
Curs, L. S., Commonwealth Edison Company, Chicago, Ill.
Dahl, F., Century Electric Company, St. Louis, Mo.
Daly, J. E. (Member) State Trade School, Hartford, Conn.
de Gaetano, G. J., 281 South Columbus Avenue, Mt. Vernon, N. Y.
De Lellis, J. (Member) Consolidated Edison Company of New York Inc., New York, N. Y.
Dembowski, A. G., University of Michigan, Ann Arbor.
Dent, W. E. Jr., Tennessee Electric Power Company, Chattanooga.
De Paolo, P. A., West Coast Power Company, Portland, Ore.
Dockar, J. F., Electric Power Equipment, Ltd., Vancouver, B. C., Canada.
Donnelly, L. B., American Telephone and Telegraph Company, Laramie, Wyo.
Dougherty, H. P., Southwestern Bell Telephone Company, Tulsa, Okla.
Dublin, L. I., Brooklyn Edison Company, Inc., Brooklyn, N. Y.
Dunlop, W. W., Pacific Telephone and Telegraph Company, Sacramento, Calif.
Eastby, M. S., Sinai, S. D.
Eckel, C. H., Humble Oil and Refining Company, Houston, Texas.
Edman, C. A., General Electric Company, Schenectady, N. Y.
Egan, G. F., Allis-Chalmers Manufacturing Company, West Allis, Wis.
Ewell, M. M., Westinghouse Electric and Manufacturing Company, Portland, Ore.
Fehr, R., General Electric Company, Schenectady, N. Y.
Fisher, G. W., (Member) Kansas Gas and Electric Company, Wichita, Kansas.
Fister, E. J., The Pennsylvania Railroad, Juniata, Pa.
Foster, W. W., Kentucky and West Virginia Power Company, Ashland, Ky.
Freeman, G., Cresaptown, Md.
Freund, W. H., RCA Radiotron Company, Harrison, N. J.
Gadino, W. J., Crocker Wheeler Electric Manufacturing Company, Ampere, N. J.
Gentry, P. B., Southwestern Bell Telephone Company, Tulsa, Okla.
Gleason, L. L., Puget Sound Power and Light Company, Seattle, Wash.
Goldsmith, A., Armour Institute of Technology Chicago, Ill.
Good, D. B. (Member) Texas Empire Pipe Line Company, Tulsa, Okla.
Gordon, D., 4145 North Troy St., Chicago, Ill.
Graham, W. R., Ohio Brass Company, Mansfield, Ohio.
Hall, C. F., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Halligan, E. P., Public Service Company of Northern Illinois, Wheaton, Ill.
Hansen, T. N. Jr., General Electric Company, Schenectady, N. Y.
Harder, M. N., Bureau of Power and Light, Los Angeles, Calif.
Haun, B. O. Jr., Emerson Electric Manufacturing Company, St. Louis, Mo.
Hazen, H. E., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Herklotz, E. A., Signal Corps Laboratories, Ft. Monmouth, N. J.
Hildenbrand, H. L., Esterline-Angus Company, Indianapolis, Ind., Wilkinsburg, Pa.
Hodges, J. R., Southern California Edison Company, Long Beach, Calif.
Hoffman, R. C., General Electric Company, Schenectady, N. Y.
Hoffmann, E. H., United Gas Pipe Line Company, Houston, Texas.
Honeycutt, M., General Electric Company, Schenectady, N. Y.
Hughes, S. B. (Member) Northwestern Bell Telephone Company, Omaha, Nebraska.
Jessup, W. T., General Electric Company, Schenectady, N. Y.
Johnson, B. W., Western Electric Company, Inc., Cicero, Ill.
Johnson, G. B., Northwestern Bell Telephone Company, Minneapolis, Minn.
Johnson, J. D., General Electric Company, Schenectady, N. Y.
Jones, L. G., Otis Elevator Company, Seattle, Wash.
Jones, T. B., Bell Telephone Laboratories, Incorporated, New York, N. Y.
Justin, F. H., Dow Chemical Company, Midland, Mich.
Kalish, D., Alliance Manufacturing Company, Alliance, Ohio.
Keck, M. W., Toledo Edison Company, Toledo, Ohio.
Keppy, J. C., Bell Telephone Company, Toronto, Ont., Canada.
Kirby, M. J., General Electric Company, Schenectady, N. Y.
Klebanoff, M. M. (Member) 225 11th Avenue, San Francisco, Calif.
Kreiberg, T. N., Pacific Scientific Corporation, San Francisco, Calif.
Lacefield, S., Louisville Gas and Electric Company, Louisville, Ky.
Lattin, R. B. (Member) Rockbestos Products Corporation, New Haven, Conn.
Light, P., Bureau of Agricultural Economics, Washington, D. C.
Linch, W. E., General Electric Company, Pittsfield, Mass.
Loughridge, T. J., Humble Oil and Refining Company, Baytown, Texas.
Luginbill, W. F., Michigan Bell Telephone Company, Battle Creek, Mich.
Lundberg, H. G., General Electric Company, Schenectady, N. Y.
Macgurn, R. B., Durham Telephone Company, Durham, N. C.
Magnusson, P. C., International House, Berkeley, Calif.
Mapother, E. H., Mica Insulator Company, Cleveland, Ohio.
Marburger, T. E., Gas and Electric Company of Baltimore, Baltimore, Md.
Martinez, J. D., Roller-Smith Company, Bethlehem, Pa.
Masin F. Jr., fire department, New York, N. Y.
Maxim, J. H., General Electric Company, Schenectady, N. Y.
Maximoff, B. S., General Electric Company, Schenectady, N. Y.
McCauley, C. Jr., Century Electric Company, St. Louis, Mo.
McCullough, J., Westinghouse Electric and Manufacturing Company, Emeryville, Calif.
McEachron, K. B. Jr., General Electric Company, Schenectady, N. Y.
Mead, M. S. Jr., General Electric Company, Schenectady, N. Y.
Mencher, I., Garden State Electric Company, Elizabeth, N. J.
Mendelsohn, L., General Electric Company, Pittsfield, Mass.
Menear, W. R., Bell Telephone Company of Pennsylvania, Greensburg, Pa.
Miles, J. A., Memphis Light and Water Division, Memphis, Tenn.
Montfort, L. R., Bell Telephone Laboratories, Incorporated, New York, N. Y.
Moon, C. L., Stanolind Pipeline Company, Tulsa, Okla.
Morten, R. K., 1630 North Main Street, Los Angeles, Calif.
Muller, A. L., Aluminum Company of America, Tapoco, N. C.
Nelms, W. L. Jr., General Electric Company, Orangeburg, S. C.
Noddings, W. C. (Member) Raritan Copper Works, Perth Amboy, N. J.
Nowak, O. J., New York Telephone Company, New York, N. Y.
Nuckols, W. D., Community Public Service Company, Ft. Worth, Texas.
Palmer, R. L. (Member) International Bus Machine Corporation, Endicott, N. Y.
Pashby, R. W., Micro Switch Corporation, New York, N. Y.
Pearson, H. T., Commonwealth Edison Company, Chicago, Ill.
Perrine, R. O. (Member) Cutler Hammer, Inc., Milwaukee, Wis.
Poe, L. H. (Member) Ebasco Services, Inc., New York, N. Y.
Pohr, H. R., Cleveland Electric Illuminating Company, Cleveland, Ohio.
Poulterer, W. T. (Member) Simplex Wire and Cable Company, New York, N. Y.
Pursell, W. L., Skelly Oil Company, El Dorado, Kans.
Rankin, A. W., General Electric Company, Schenectady, N. Y.
Reed, R. H., Loup River Public Power District, Columbus, Nebr.
Reese, O. L., City Lighting Department, Seattle, Wash.
Ricker, G. O., Memphis Power and Light Company, Memphis, Tenn.
Riggert, M. C., General Electric Company, Cleveland, Ohio.
Robinson, J. A., Western Electric Company, Kearny, N. J.
Rosquist, H. T., Standard Oil Company of New York, Brooklyn, N. Y.
Schlitt, W. J., Ideal Electric and Manufacturing Company, Mansfield, Ohio.
Schmitt, C. D., Fairbanks Morse and Company, Beloit, Wis.
Semm, P. T., 1019 South Summit Avenue, Sioux Falls, S. D.
Sharp, W. S., Pulp Products Company, Massillon, Ohio.
Shemet, A. M., Western Electric Company, Inc., New York, N. Y.
Shirling, G. K., Southwestern Bell Telephone Company, Kansas City, Mo.
Short, W. G., General Electric Company, Portland, Ore.
Sibila, K. F., The Ohio Crankshaft Company, Cleveland, Ohio.
Simonetta, F. R., Pacific Gas and Electric Company, Red Bluff, Calif.
Skinner, J. H., Federal Shipbuilding & Dry Dock Company, Kearny, N. J.
Southern, C. M. (Member) Atlantic Pipe Line Company, Dallas, Texas.
Southwell, J. D., City of Beaumont, Beaumont, Texas.
Sperow, L. H., General Electric Company, Schenectady, N. Y.
Stebbings, R. W., Illinois-Iowa Power Company, Champaign, Ill.
Stewart, J. A., Illinois Bell Telephone Company, Chicago, Ill.
Storm, C. P., Sanitary District of Chicago, Chicago, Ill.
Sukaskas, J. A., in care of Shellan, 4323 9th Avenue, Brooklyn, N. Y.
Thompson, E. C., Ohio Brass Company, Mansfield, Ohio.
Thurman, A. L., General Electric Company, Schenectady, N. Y.
Tirrell, C. W., Associated Telephone Company Ltd., Santa Monica, Calif.
Tovee, E. H., Canadian Westinghouse Company, Ltd., Hamilton, Ont., Canada.
Trbovich, N., Inland Steel Company, East Chicago, Indiana.
Trotman, H. C., Western Electric Company, Kearny, N. J.
Vail, C. R., General Electric Company, Pittsfield, Mass.
Wager, A., Bisemann Magneto Corporation, Brooklyn, N. Y.
Wagner, C. H. Jr., Phelps Dodge Copper Products Corporation, New York, N. Y.
Washinsky, F. G., Peerless Laboratories, New York, N. Y.
Waterman, A. F., Commonwealth Edison Company, Chicago, Ill.
Watts, R. P., Carolina Aluminum Company, Tapoco, N. C.
Weinstein, H. L., General Electric Company, Philadelphia, Pa.
Weist, W. C., General Motors Corporation, Dayton, Ohio.
Wesel, W., Gibbs & Hill, New York, N. Y.

Whinnery, J. R., General Electric Company, Schenectady, N. Y.
White, W. B., Westinghouse Electric and Manufacturing Company, Charlotte, N. C.
Wichman, A., (Member) 236 Quincy Avenue, New York, N. Y.
Wilder, R. D., Public Service Electric and Gas Company, Newark, N. J.
Williams, S. B., Bell Telephone Laboratories, Incorporated, New York, N. Y.
Winslow, R. A., Westinghouse Electric and Manufacturing Company, Sharon, Pa.
Woodruff, J. P., Tennessee Valley Authority, Columbia, Tenn.
Woodward, J. P., General Electric Company, Erie, Pa.
Worley, L. E., Tennessee Electric Power Company, Chattanooga, Tenn.
Wyckoff, P. H., Westinghouse Electric and Manufacturing Company, East Pittsburgh, Pa.
Yost, J., Long Island Lighting Company, New York, N. Y.
Zerby, A. B., Eta Kappa Nu Association, Dillsburg, Pa.
Ziemann, A. E., General Electric X-Ray Corporation, Chicago, Ill.
Zwinakis, J. A. Jr., Landers, Frary, and Clark, New Britain, Conn.

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Foreign

Hughes, W., Christchurch Technical College, Christchurch, New Zealand.
Vilacha, F. A., Maiquetia, Venezuela.
Cuffe, R. C., Irish Free State Electricity Supply Board, Dublin, Ireland.
Diaz, R. A., Hotel Vanderbilt, Havana, Cuba.
Gillespie, M. L., Messrs. Johnson and Phillips, Johannesburg, South Africa.

5 Foreign

Engineering Literature

New Books in the Societies Library

Among the new books received at the Engineering Societies Library, New York, recently are the following which have been selected because of their possible interest to the electrical engineer. Unless otherwise specified, books listed have been presented gratis by the publishers. The Institute assumes no responsibility for statements made in the following outlines, information for which is taken from the preface of the book in question.

(The) COLLECTED PAPERS of GEORGE ASHLEY CAMPBELL. New York, American Telephone and Telegraph Company, 1937. 548 pages, illustrations, 11 by 7 inches, cloth, apply. Dr. Campbell's contributions to the development of electrical communication have been numerous and fundamental, his work upon telephone circuit loading and electric wave-filters being especially noteworthy. This volume, published to commemorate his retirement from active service with the American Telephone and Telegraph Company, collects his published papers in convenient form, with a foreword by Doctor Vannevar Bush and an introduction by Doctor E. H. Colpitts.

ASTM STANDARDS on ELECTRICAL INSULATING MATERIALS, prepared by Committee *D*-9 on Electrical Insulating Materials. November, 1937. Philadelphia, American Society for Testing Materials. 373 pages, illustrated, 9 by 6 inches, paper, $2.00. Contains the current report of the committee on electrical insulating materials and the methods which the Society has developed for testing the various products in that field.

MacRAE'S BLUE BOOK and HENDRICK'S COMMERCIAL REGISTER. 45 editions, 1937–38. Chicago and New York, MacRae's Blue Book Company, 1937. 3,580 pages, illustrations, 11 by 8 inches, cloth, $15.00. An annual volume listing manufacturers and sources of supply of manufactured products in the United States.

LECTURES on the MATHEMATICAL THEORY of ELECTRICITY. By F. B. Pidduck. Oxford, England, Clarendon Press; New York, Oxford University Press, 1937. 110 pages, diagrs., tables, 9 by 6 inches, cloth, $3.25. An abridgement of a course of lectures delivered to mathematical students to supplement other reading. The material deals with static electricity and magnetism, electromagnetic theory, Maxwell's equations and some of their applications.

Great Britain, Mines Department. Report of H. M. ELECTRICAL INSPECTOR of MINES for the year 1936. London, His Majesty's Stationery Office, 1937. 105 pages, illustrations, 10 by 6 inches, paper, (obtainable from British Library of Information, 270 Madison Ave., New York, $0.55). Report includes inspections, use of electricity in mines, statistics and descriptions of accidents connected with use of electricity, types of machinery utilizing electricity, and signaling.

5,000 YEARS of GLASS. By F. Rogers and A. Beard. New York, Frederick A. Stokes Company, 1937. 303 pages, illustrations, 9 by 6 inches, cloth, $2.50. A popularly written history of glass from the earliest known manufacture to modern practice. It covers the development of glass making processes and glass coloring, with separate chapters on gas and electric light bulbs, lenses, and mirrors.

DIMINISHING RETURNS and PLANNED ECONOMY. By G. M. Peterson. New York, Ronald Press Company, 1937. 254 pages, illustrations, 9 by 6 inches, cloth, $3.00. A textbook of economics presenting a method of analysis useful in teaching the fundamental principles. Its main contribution is a graphic analysis of the law of diminishing returns, showing the relation of this law to numerous other economic concepts often considered independent.

BUSINESS ADMINISTRATION for ENGINEERS. By C. F. Harding and D. T. Canfield. New York and London, McGraw-Hill Book Company, 1937. 637 pages, diagrs., charts, tables, 9 by 6 inches, cloth, $5.00. Intended to assist the young engineer in correlating engineering with business, this book sets forth in the engineer's language, the organization, economic and managerial problems of the industries and public utility corporations with which he is likely to be associated.

ALLGEMEINE und TECHNISCHE ELEKTROCHEMIE NICHTMETALLISCHER STOFFE. By R. Müller. Vienna, Julius Springer, 1937. 440 pages, illustrations, 9 by 6 inches, cloth, 30 rm. A treatise on the electrochemistry of nonmetallic substances. The separation of metalloids at the anode is considered at length. Following this come sections on cathodic reduction of nonmetallic substances and on anodic oxidation. The last section covers electrophoresis, electroendosmosis, and electrodialysis.

ASTM STANDARDS on TEXTILE MATERIALS. Prepared by Committee *D*-13 on Textile Materials. September 1937, Philadelphia, American Society for Testing Materials. 306 pages, illustrated, 9 by 6 inches, paper, $2.00; $1.25 to members. Contains material on methods of testing, definitions, terms, and specifications for textile materials.

(An) INTRODUCTION to PROJECTIVE GEOMETRY. By C. W. O'Hara and D. R. Ward. Oxford, England, Claredon Press; New York, Oxford University Press, 1937. 298 pages, diagrams, 9 by 6 inches, cloth, $4.00. An account of the fundamental concepts and methods of projective geometry in two dimensions, both synthetic and algebraic.

TRANSFORMER PRINCIPLES and PRACTICE. By J. B. Gibbs. New York and London, McGraw-Hill Book Company, 1937. 210 pages, illustrated, 9 by 6 inches, cloth, $2.50. A nonmathematical description of single-phase and three-phase transformers, autotransformers and instrument transformers, covering related problems such as transformer insulation, oil, coils and cores, cooling, testing, ratio adjustment, and phase transformation.

TASCHENBUCH für FERNMELDETECHNIKER. By H. Goetsch. 6th edition. Munich and Berlin, R. Oldenbourg, 1937. 740 pages, illustrated, 8 by 5 inches, cloth, 16 rm. A handbook on communication engineering, covering electrical systems for producing effects at a distance, radio excepted.

1937 SUPPLEMENT to BOOK of ASTM STANDARDS. Philadelphia, American Society for Testing Materials, 1937. 272 pages, illustrated, 9 by 6 inches, paper, $2.00 (free to all who purchased copies of Standards). Forty-four standards (new, replacements, or revisions), adopted since the appearance of the 1936 edition of the triennial Book of Standards.

PHYSICS in INDUSTRY. New York, American Institute of Physics, 1937. 290 pages, illustrated, 8 by 5 inches, cloth, $1.50. A collection of articles by industrial physicists demonstrating the importance of physical training and research in various large industries.

MODERNE MEHRGITTERELEKTRONENRÖHREN, Bd. 1. Bau, Arbeitsweise, Eigenschaften. By M. J. O. Strutt. Berlin, Julius Springer, 1937. 151 pages, illustrated, 10 by 6 inches, paper, 12.60 rm. A treatise on modern multigrid electron tubes, divided into three sections: high-frequency amplifying tubes, mixing tubes, and tubes of low-frequency amplification. Covers history, operation, characteristics, physical and technical properties, and phenomena arising in use.

INTRODUCTION to the THEORY of FOURIER INTEGRALS. By E. C. Titchmarsh. Oxford, England, Claredon Press; New York, Oxford University Press, 1937. 390 pages, tables, 10 by 6 inches, cloth, $6.00. An account of the elements of the theory of Fourier integrals.

INTRODUCTION to MATHEMATICAL PROBABILITY. By J. V. Uspensky. New York and London, McGraw-Hill Book Company, 1937. 411 pages, tables, 9 by 6 inches, cloth, $5.00. Intended to give students the fundamentals of the theory of probability and a fairly comprehensive statement of its more important methods and results.

HOOVER POLICIES. By R. L. Wilbur and A. M. Hyde. New York, Charles Scribner's Sons, 1937. 667 pages, tables, 10 by 6 inches, cloth, $3.00. Mr. Hoover's governmental policies presented by two members of his cabinet. Includes social, labor, agriculture, tariff, conservation, public works, business regulation, banking reform, and foreign policies; also a section on the depression and relief methods.

Die ELEKTRISCHEN MESSINSTRUMENTE. (Sammlung Göschen 477). By I. Herrmann. 4th edition. Berlin and Leipzig, Walter de Gruyter and Co., 1937. 137 pages, illustrated, 6 by 4 inches, cloth, 1.62 rm. A general treatise on electrical measuring instruments: adjustable-coil, magnetic needle, induction, thermal, and vibration.

EFFECT of IMPURITIES in COPPER. By S. L. Archbutt and W. E. Prytherch. London, British Non-Ferrous Metals Research Association, 1937. 134 pages, illustrated, 10 by 6 inches, cloth, 12s. 6d. Collected results of a research on the effects of impurities on the working, mechanical, electrical, and other properties of copper.

DIFFERENTIALGEOMETRIE, volume 1. Raumkurven und Anfänge der Flächentheorie. (Sammlung Göschen Nr. 1113). By R. Rothe. Berlin and Leipzig, Walter de Gruyter and Company, 1937. 132 pages, diagrams, tables, 6 by 4 inches, cloth, 1.62 rm. Material covered includes the analytical construction of space curves and surfaces, tangents, warped surfaces, differential invariants, line elements, cutting angles, and various basic equations.

COST ACCOUNTING, Principles and Methods. By C. Reitell and C. E. Johnston. 2 edition. Scranton, International Textbook Company, 1937. 425 pages, charts, tables, 10 by 6 inches, cloth, $3.50. Contains sections on basic cost principles, manufacturing cost elements, process and job-order cost systems, standard costs and budgets, and executive use of costs.

CENTRAL STATIONS. By T. Croft, revised by G. H. Hall. 3 edition. New York and London, McGraw-Hill Book Company, 1937. 360 pages, illustrated, 8 by 6 inches, cloth, $3.00. A practical manual for the central-station electrician. In addition to a nonmathematical presentation of scientific fundamentals, discusses all phases of generation, transmission, and distribution, as practiced today.

ARMATURE WINDING. By D. F. Moreton, C. H. Dunlap, and L. R. Drinkall. Chicago, American Technical Society, 1938. Illustrated, 9 by 6 inches, cloth, $2.00. A practical manual on the construction, winding, and repairing of a-c and d-c motors and generators. Describes theory and procedure, with practical connection diagrams, including a special set of diagrams for induction motors.

Engineering Societies Library

29 West 39th Street, New York, N. Y.

MAINTAINED as a public reference library of engineering and the allied sciences, this library is a co-operative activity of the national societies of civil, electrical, mechanical, and mining engineers.

Resources of the library are available also to those unable to visit it in person. Lists of references, copies or translation of articles, and similar assistance may be obtained upon written application, subject only to charges sufficient to cover the cost of the work required.

A collection of modern technical books is available to any member residing in North America at a rental rate of five cents per day per volume, plus transportation charges.

Many other services are obtainable and an inquiry to the director of the library will bring information concerning them.

Transactions

Papers and Discussions Comprising Pages 61–114 of the 1938 Volume

The PCC Street Car

By C. F. HIRSHFELD

FELLOW AIEE

Synopsis: This car is the result of a collective effort to modernize and improve the street car. Its development was preceded by extensive investigation directed toward determining the characteristics of conventional cars and the ways in which and extents to which these should be modified to approach the ideals of street-railway executives and of the riding public, respectively. Car and equipment designs were then produced. These represent the best technical approach to these ideals which could be reached within the economic limitations which exist. The car has been made more agile, has been given better appearance and better performance in many respects which affect the passenger. In spite of the addition of equipment not used in the older cars and of many refinements of design it is obtainable at a price which appears to meet the economic requirements. Over 500 of these new vehicles are already in use in seven cities of this country.

THE VEHICLE which has become known as the PCC car is the product of several years of intensive research and development. The effort was initiated and sponsored by executives of leading street-railway companies. They realized the extent to which basic improvements in street cars had lagged behind the development of other vehicles available for both private and public transportation, and the undesirable effect this was having upon street-railway revenues. They believed that street cars must continue in use on certain routes and under certain conditions but they realized that the conventional street car fell far short of requirements.

These executives formed Electric Railway Presidents' Conference Committee as an instrumentality through which a modernized car might be developed. Abbreviation reduced this lengthy name to Presidents' Conference Committee and ultimately to PCC.

The assignment given the engineering staff of PCC was to determine whether the street car could be improved radically and, if so, how. One of its first endeavors was the determination of what were considered the faults in, and shortcomings of the conventional cars; and the characteristics which it was thought an ideally perfect car should possess. In this part of the investigation street-car operators and street-car users were consulted. In fact, interviews were also had with individuals who might have been passengers but were not.

One result of this investigation was the enumeration of a number of objectives of physical character. The principal ones were:

1. Great agility. This means ability to maintain high schedule speed in the face of frequent stops.
2. Modern appearance.
3. Low noise level, both inside and outside the car.
4. Good riding quality. This refers to the absence of high-frequency vibrations, the absence of repetitive low-frequency movements of objectionable sorts, and the absence of jerks or jolts.
5. Good ventilation.
6. Good illumination.
7. Minimum wear and tear of road bed.

Another result of the investigation was an enumeration of certain economic factors within the limitations of which the desired physical characteristics had to be obtained. These economic factors were:

1. Low first cost.
2. Low operating cost.
3. Low maintenance expense.

It is interesting to note that, as in the case of many of the older industries, little factual information of a technical character was available with respect to the performance of conventional equipment. The performance of representative cars in different respects had to be determined in order to establish what may be called points of departure. Frequently it was even necessary to develop instruments and test methods. Outstanding examples are furnished by the problems presented in attacking such important factors as riding quality and noise level. In a few cases it was found desirable to experiment on human beings to determine certain characteristics as, for example, their tolerances for different kinds of motion.

In the later design of new equipment the ideals determined by these early investigations served as the goals to be approached as nearly as technical ability and economic considerations permitted. An account of the methods adopted and, to some extent, the degree of success achieved forms the bulk of this paper.

Paper number 37-121, recommended by the AIEE committee on transportation and presented at the AIEE winter convention, New York, N. Y., January 24–28, 1938. Manuscript submitted November 10, 1937; made available for preprinting December 3, 1937.

C. F. HIRSHFELD is chief engineer of the Transit Research Corporation, Detroit, Mich., and chief of research of The Detroit Edison Company.

1. For all numbered references, see list at end of paper.

Great Agility

It is well known that the schedule speed attainable with street cars operating with frequent stops is determined almost entirely by the number of stops, the average length of stop, and the speed of starting and of stopping. The maximum attainable speed is of little consequence except in the case of long, uninterrupted runs.

The number of stops is a function of the passenger capacity of the car and the characteristics of the route on which it is operating. Once the size of car is determined, the designer has practically no control over the number of stops. The designer can however control the length of stop to a limited extent. For example, ease of entering and of leaving the car naturally tend to speed up passenger movement and thus to decrease the length of stop required to load or unload a given number of passengers.

This has been recognized in this case. Steps have been made to approach the proportions used in houses and office buildings to the extent that certain limiting conditions permitted. Effective illumination has been provided for the stepwells and the adjacent street area so as to facilitate mounting and demounting. Moreover, the illumination is so arranged as not to produce glare in the eyes of the moving passengers. The flow of passengers into and out of cars was studied and the PCC design provides as far as possible for natural flow, that is movement along the lines most naturally followed by the passenger. The seating arrangement is such as to provide the maximum practicable amount of open floor space in the front half of the car so as to permit ready movement toward the rear and ready access to the central exit doors. Stanchions and handrails are so arranged that there shall always be a handhold of some sort within easy reach of any passenger so as to encourage passenger movement while the car is in motion. Moreover, the handholds are so arranged that they afford a convenient hold for persons of all heights. Every effort was made to shorten the time of stops by these and similar methods. However, at best, the possible improvement of schedule speed by such methods is decidedly limited.

The greatest possibilities lie in increased speed of starting and stopping. Anyone who has watched the conventional street car during its slow and deliberate start will have observed the way in which the more agile automotive vehicles glide ahead of it, pre-empt its track and hold it down to a sedate but unacceptable rate of progress. Anyone who has watched the operation of the car in traffic will have observed how the operator is continuously throwing off power and applying his brakes in anticipation of a possible collision or the approach to an intersection at which he must stop. If the street car is to make reasonably high schedule speeds under modern conditions it must be capable of starting and stopping at rates comparing favorably with those of automotive traffic.

All this is well-nigh axiomatic. But a very vital question presents itself when one has arrived at this point. How rapidly can a standing human being be put into motion or brought to rest without excessive danger of accident? When this work was undertaken no one seemed to know the answer. It was decided to determine the tolerance of standing human beings for accelerating forces.

The results of this investigation have been published elsewhere.[1] Suffice it to record here that experiments were performed on standing passengers who were not holding onto any form of support. It was found they could tolerate the forces required to take them from a state of rest to an acceleration of 4.75 miles an hour per second in one second and to maintain the higher rate for two seconds or more. It was necessary only that the force be steadily applied; that is, there may be no marked and sudden variation in force during the entire process.

Tests on conventional cars showed that the forces applied to the passengers during acceleration fell far short of meeting this requirement, even when the automatic types of control were used. A variation of 50 to 100 per cent in very short time periods was not at all uncommon.

A performance specification was prepared which called for a constant increase of acceleration from zero to 4.75 miles an hour per second in one second, the maintenance of the higher value for two seconds and the maximum practicable approach to constant power input thereafter. After some experience this was modified to permit a lower rate of increase for a very short time at the start of the accelerating process. It was found that this arrangement was more acceptable to the passengers.

Equipment has been produced which approximates this performance specification very closely. It is now in use on over 500 cars in regular service in seven different cities and appears to produce results acceptable to the passengers. Certainly the car is much better able to take and hold its place in a stream of traffic.

With the starting process settled, there remained the method to be used for stopping. Experience with experimental cars showed there was no value in quick starting ability unless equal or greater stopping ability were provided. An operator would not avail himself of the ability to move fast unless certain that he could stop sufficiently quickly to avoid a collision with vehicles or pedestrians.

The maximum braking rate attainable with wheel to rail adhesion is well known and was not found adequate. Consequently magnetic track brakes were included in the braking equipment. The braking force produced by these devices is obviously independent of the coefficient of adhesion between wheels and rails and may be made additive to braking produced by the wheels.

The car is equipped with three different braking systems. These are: dynamic brakes dependent upon the use of the motors as generators; air-operated wheel-tread brakes; and magnetic track brakes. A service stop is normally made with the dynamic brakes supplemented by the tread brake as the dynamic brake "fades." At any time the operator can bring into use the track brake to increase the braking effect.

Normal or service braking is almost the reverse of the starting sequence. The deceleration increases at a constant rate to a desired value. After that it is maintained constant for the desired period and finally is decreased at a constant rate to zero value as the car comes to rest. The maximum deceleration attainable is between 8 and 9 miles

an hour per second, depending upon rail condition and other variables. This has proved sufficiently high to yield safe operation and that feeling of security on the part of the operator which is necessary to the attainment of high schedule speed.

Acceleration and braking are produced by foot pedal operation as in an automobile. The operator need not know how the pedals operate the control equipment. He need only know that further depression of either one of them produces more of the effect which that one controls, and that too sudden application or release of pressure will produce uncomfortable jolts. The mechanism is capable of giving smooth performance if properly maintained. The necessary manipulation is simple and easily learned.

The balancing speed of the car is about 40 miles per hour. While of little significance in congested urban traffic, this speed is of value in the outlying districts where it can be used.

Modern Appearance

The airplane and the automobile have given the public certain ideas with respect to the appearance of an up-to-date vehicle. They have created what may be called a style. In the light of this style the conventional street car has a decidedly antiquated appearance and the public attributes antediluvian characteristics. It is obviously desirable that a modernized car should appear as such to the public which is expected to accept and patronize it.

The car has been given automotive appearance with respect to the major lines and all obvious fittings and decoration. Front and rear vestibule hoods are formed of metal as in the case of the automobile, and to similar lines. The letterboard has been corrugated to break its flat appearance and to produce an idea of motion. It runs by easy curves into the roof structure, just as the corresponding part does in the automobile. The windshield and the vestibule corner posts are enlarged versions of good automotive practice. The over-all height of the car has been materially decreased and a suggestion of "streamlining" has been introduced. The windows are arranged to produce group effects and they have rounded corners.

It is important to note that the matter of appearance was not treated separately. Innovations have been made with an eye to reduction in weight and to the production of a vehicle mechanically better adapted to its task. There should therefore be some lasting value in the changed appearance.

Low Noise Level

The greater part of the noise made by conventional street cars originates at the wheel-rail contact and at metal-to-metal contacts in the trucks. These noises are not only broadcasted at the points of origin but are also transmitted through the metal of the truck to the car body which in turn serves as a huge sounding board.

The general principles adopted for the suppression of noise may be described as maximum practicable suppression at the source and the minimum practicable transmission from that source. The steel tire was retained of necessity. But it is supported in rubber within the wheel in such a way that noise generated at the contact with the rail is absorbed in that rubber to the maximum practicable extent. The truck is so designed as to substitute rubber articulation for metal-to-metal contacts. Thus wear and accumulation of lost motion, with resultant noise, are prevented and rubber is used to break the otherwise continuous metal paths through which the sounds would be transmitted. The use of rubber in this way has been carried to the extent of eliminating steel car springs completely and using specially designed rubber springs instead.

These and other departures and refinements have both materially reduced the noise level and made the remaining noise of more acceptable quality.

Good Riding Quality

When this work was undertaken there was little information available with respect to the tolerance of human beings for vibrations of different magnitudes and frequencies, and oriented in different directions. An attempt was made to obtain sufficient information to serve as a guide in the design of a better car. The results have been published[2–4] and need not be detailed here.

Two types of vibration or disturbance came up for consideration. These may be called high frequency and low frequency although there is no sharp demarcation. The high-frequency disturbances are practically all in the audible range; that is above 20 to 25 per second. The low-frequency disturbances are of the order of 0.2 to 5 per second.

Space does not permit a lengthy explanation nor a detailed account of the methods used to bring about acceptable conditions. The high-frequency vibrations were almost completely eliminated by abandoning the use of the conventional leaf spring and substituting the rubber spring referred to above; and by designing certain parts of the structure stiffer than had been customary. The lower-frequency vibrations and disturbances of an objectionable sort were minimized by the design of the springing system and by a radically new method of suspending the axle in the truck.

The results obtained have been checked by adequate instruments throughout the entire development. There is therefore no question regarding the extent of the improvement. Recording accelerometers adapted to measure accelerations in the three principal directions show the floor of this car to vibrate very little, through very small amplitudes, and at very low frequencies. Such movements as do occur are characterized by low accelerations so that the record is a wavy instead of a jagged line. The conventional cars give very jagged records, showing numerous high and low frequencies of large amplitude superposed so as to produce "beats" which further aggravate the situation.

Closely associated with good riding quality is reasonable freedom from jolts caused by operation of motor control and of brakes. This has been referred to above. The equipment provided is such that a moderately careful

operator can produce remarkably smooth operation without having to possess exceptional skill.

Good Ventilation

The ventilating and heating arrangements are combined into one system. Motor and brake control resistors are enclosed in a compartment under the center of the car where they are protected from the weather. A motor-driven fan blows over these resistors the quantity of air required to maintain them at a safely low operating temperature. During the heating season more or less of this air, as required, is blown into the car after being warmed by passing over the resistors. What is not needed to maintain the car temperature is wasted through thermostatically controlled dampers.

The air handled by the fan is drawn from the car interior through ducts which form part of the car structure. This air enters the car by different routes. Part of it enters by leakage around doors and at other places. Part of it enters through a roof ventilator so designed that the quantity passed increases with car speed. During the heating season part of it is blown in by the fan as above described and is in reality recirculated.

The total quantity of air passing through the car interior varies with conditions. The minimum aimed at is 1,200 cubic feet per minute. This is, in fact, a very generous supply when considered in terms of building ventilation.

Good Illumination

Illuminating engineers have consistently urged greater intensity of artificial illumination in the interest of less eye fatigue and greater health. Vehicle illumination has commonly been of the order of 2 to 5 foot candles on the passenger's reading plane. Office illumination has seldom been greater than 10 foot candles on the table or desk top although recent installations have shown a tendency toward at least doubling this figure.

Recognizing that the public of this country reads extensively while riding and that at best there will be a certain amount of uncontrollable movement of the printed surface with respect to the eye, it seems reasonable to conclude that a high degree of illumination should be provided in mass transportation vehicles. A value of 15 foot candles on the reading plane of the seated passenger was chosen in this case, with provision for raising it to 20 if later found desirable.

Two difficulties are encountered when attempting a high intensity of illumination in a street car. First, the ceiling is necessarily low and it is difficult to install thereon or therein sources of illumination capable of giving the desired standard of lighting without producing at the same time most objectionable and nerve racking glare. This difficulty has been at least partly surmounted by the development of new types of fixtures and methods. Completely indirect lighting is capable of producing a technically satisfactory result but it is undesirably expensive both as to first cost and as to operation. Lens types and louver types of lighting fixtures have thus far offered the most satisfactory solutions.

The second difficulty arises from the fact that the human eye adjusts itself rather slowly when one goes from an area of high illumination intensity to one of low intensity. Every passenger must ultimately alight from the car. If this involves stepping into a poorly illuminated street from a brightly illuminated car the passenger is temporarily almost incapable of seeing sufficiently clearly to guard against accident. The intensity chosen, combined with a reasonably high illumination of the street surface outside the exit door by means of car lighting, appears to be within safe limits.

Minimum Wear and Tear of Road Bed

The action of a rolling vehicle upon a road bed is not yet completely understood in a technical sense. It is known that the wear and tear increases with increasing weight of the unsprung parts and with increasing weight of the vehicle, all other things being equal. It is also known that it increases at a rapid rate if the assembly of masses and springs happens to be resonant to a frequency that can be imposed by the road bed, as for example rail joints or pavement joints. It is also known that violent movements of the vehicle, such as "nosing" and "galloping" tend to rapid destruction of the road bed.

In the present case all these facts were taken into consideration in the design of the vehicle. The completely unsprung weight consists of the wheel tread combined with part of the disk of the wheel whereas in the conventional car it consists of the entire axle assembly and a large fraction of the motor. The weight of the trucks, including the rather heavy magnetic track brakes, is somewhat less than that of conventional trucks without such brakes. The weight of the complete vehicle is 33,000 pounds against figures of the order of 38,000 to 45,000 for the later cars of conventional design. It is believed that refinement of design may bring the weight to a figure nearer 30,000 pounds. The present weight is achieved with steel construction. If the economics of the situation should ultimately show that the extensive use of lightweight alloys can be justified, the total weight could be reduced drastically; in fact a reduction of two to three tons is not inconceivable.

Resonance and violent movements have been minimized by careful attention to the dynamics of the assembly and by certain innovations in truck design, including the new suspension of the axle in the truck referred to above.

Economic Considerations

It has been stated that the technical improvements that have been reviewed briefly in the preceding paragraphs had to be achieved within certain economic limitations. Obviously a technically perfect car would be of no value to the industry if it did not also possess such characteristics as to make it economically usable. The following paragraphs are devoted to these economic factors.

Low First Cost

The street car is only one of several types of vehicle available for mass transportation. Each type has certain physical and economic characteristics which determine its proper place in a well-co-ordinated transportation system. The street railway is operated on and with structures which necessitate a considerable investment; fixed charges therefore are very significant in its economy. Its compensating advantage is that where traffic density is sufficiently high the unit cost of handling passengers is lower than in the case of any other form of surface transportation. Thus the economic field of the street car under given circumstances and in comparison with other public vehicles, such as busses, is circumscribed by the extent to which fixed charges can be limited. It follows that low first cost of vehicle is particularly important.

Much serious thought was given to the possible means of obtaining low first cost because it was known that a car which would give the desired performance would require more equipment and greater refinement of design than previously had been used in this field. That is to say, the problem was to develop a much better car saleable at a lower price. Experience in other industries pointed to standardization as one possible means. Here, however, further difficulty was injected by the very real physical differences and the limitations which exist upon the street railway properties in various cities. It is only necessary to mention by way of illustration the different track gauges in use and the limitations on external contour which result from unchangeable clearance conditions on the individual properties.

This phase of the problem was attacked by standardizing parts and sub-assemblies which, within limits, could be assembled to produce the different vehicles required by different cities while retaining most of the economics of standardized production. Thus, the body between corner posts is a standardized assembly usable without change on nearly all properties in this country and Canada. The front and rear vestibules are each standardized and are usable on all properties. A car made of the standardized body and these vestibules is usable on most properties. It is known as the "basic car." This has an overall length of 46 feet.

A property requiring a shorter car obtains it by dropping out one window panel. This shortens the car by 30 inches. A property requiring a longer car obtains it by putting a filler piece between one vestibule and the adjacent end of the car body. Such modifications of the basic car are already in use.

The standard arrangement is front entrance, center exit. It was known that other arrangements would be required on certain properties, including an additional rear exit door in one case. The structure is so designed as to make such modifications possible at minimum cost.

The truck presented a more difficult problem than did the car body. Track gauges in use vary from three feet six inches to five feet four and one-half inches. The first attempts to produce a truck design embodying the principles which had been found necessary, and still easily modifiable to fit all track gauges, were not completely successful. A design was evolved which could be used with very minor modifications on standard and wide gauges. Later a second and more flexible design was developed. This is now in use on one narrow gauge property. It can be modified very simply to adapt it to any track gauge.

As the solution now stands, the same major parts can be used in trucks of any gauge. Certain minor modifications are required. For example, the lengths of axles and of axle housings must vary with the gauge. However, the variations necessary in different parts are of such character as to entail a minimum of expense.

The method of standardization adopted has worked well in practice. Cars have been purchased at prices which make them economically usable in spite of the addition of many items and of the refined construction required to obtain the improved performance aimed at.

Low Operating Cost

The two principal factors in operating cost are platform labor and power. Probably the next most important factor is the cost of accidents; if that be included under this heading.

Provision has been made for reducing platform labor cost to a minimum through two factors, namely, providing for increased schedule speed and by designing the car for one-man operation. This does not mean that it was merely arranged for such operation; it was designed to make it possible for one man to perform all required functions with the maximum of convenience and the minimum of fatigue. Included in these provisions are foot operation of the car with respect to power and brakes; a comfortable, well placed and adequately adjustable operator's seat; a well ventilated and properly warmed operator's position; a conveniently located gang switch controlling all auxiliary functions, and numerous other details.

The power consumption per car mile is greater than that of the conventional car. The greater agility demanded brings this about as an unavoidable consequence. In addition, the requirement of maximum smoothness during acceleration further increased the power consumption through the elimination of the commonly used series-parallel type of control. The philosophy back of this step is that the performance of the car must be made acceptable to the public. If such performance requires increased power consumption the car must carry this burden. Should it prove economically unable to do so it no longer has any place on the street.

The increased power consumption is, however, offset more or less perfectly by the use of control resistor heat for car heating. In this way the annual peak demand is relatively reduced and, under the form of contract on which most street railways buy power, its cost is correspondingly reduced. It remains for experience to show to what extent this balances the increased power consumption.

It is still too early to draw conclusions with respect to accident hazards. The cars now in use are comparatively new instruments with characteristics quite different from

those of their predecessors, but operated by men who were trained in the use of the older equipment. It is however certain that the use of the magnetic track brake has made stopping much more independent of the condition of the rail and has thus reduced one well-recognized hazard.

Low Maintenance Expense

It is almost axiomatic that "wear and tear" tends to increase with speed. However, it is not necessary that they do so, in an absolute sense. One may so design that maintenance is lower at high speed than with other designs at low speed. This has been attempted in this case.

The body of the car is a completely welded structure so that it acts as a unit in contrast to riveted structures which sooner or later act as a rather loosely knit assemblage of parts. Collision experience had thus far appears to prove that this body suffers less damage and is more easily repaired than was the case with the older type of structure.

Moreover, the body is made of an assemblage of standardized and interchangeable parts, just as is an automobile. Therefore, replacement parts may be both relatively cheap and relatively cheaply installed.

Most of the electric and other moving equipment is enclosed in ventilated compartments so that it is protected from the weather and given the best chance for uninterrupted operation. All this equipment is standardized and arranged for easy removal and replacement by similar parts. To a great extent the mounting dimensions of competitive makes of equipment are standardized. It follows that in many respects maintenance can be performed by replacement of a piece of equipment with an equivalent piece so that the primary investment can be returned to service immediately. The equipment which has been removed can be transported to a bench arranged for the easy and cheap performance of the necessary maintenance operations.

Propulsion motors are supplied with ventilating air which is taken from outside the sides or the car, carried through ducts within the car-body bolster structure, and delivered to the motors through bellows connections. In this way much of the dirt that ordinarily finds its way into street-car motors is excluded. The maintenance requirements should be correspondingly reduced.

The trucks of street cars are generally responsible for high maintenance costs if they are adequately maintained. The new trucks were designed to reduce maintenance requirements and to simplify the performance of such maintenance as is required. It has already been indicated that relatively moving metal-to-metal contacts have been avoided in so far as practicable. Where they are absolutely essential, as in journal bearings and gears, provision is made for flooded lubrication and the proportions are calculated for a life of 750,000 miles. In many cases necessary articulations are made by means of rubber so arranged that distortion of the rubber within very conservative limits permits the necessary relative movements of metal parts. The principle followed in the use of rubber is to have all parts with respect to which relative motion is required literally float in rubber.

The trucks are so designed that they consist of an assemblage of standardized and interchangeable parts, readily removable from the assembly as integral units. The favorable effect upon maintenance is obvious.

Finally, as already indicated, the trucks are mounted on resilient wheels. Experiment in the laboratory and on regular street-railway equipment in the street showed that this type of wheel reduced tremendously the destructive forces to which the parts of the truck are subjected. In spite of this fact, all truck parts have been designed for operation on conventional solid wheels, so that the resultant high factor of safety should be effective in minimizing maintenance expense.

Such figures as are available to the author indicate that in spite of all the radically new features in car body and trucks and in spite of all the unforeseen and unforeseeable errors that enter into the design, manufacture and use of new equipment of this sort, the maintenance expense on these cars is now of the same order of magnitude as that of the older cars in spite of their higher schedule speeds and in spite of the lack of experience in handling them on the part of both operating and maintenance personnel. This gives ground for the belief that when initial errors in design and fabrication are eliminated, and when the personnel involved becomes more familiar with this equipment, the maintenance expense will in fact be considerably lower than that characteristic of the older forms of rolling stock.

Such, in brief, is the history and status of development of the PCC car. It certainly represents both a major technical and economic advance over the conventional vehicle previously available. Even so, it must be considered only one more link in a practically endless chain of improvement. The heads of those who produced this product are already filled with visions of the further steps that might be taken. The present product is in reality a modernization and refinement of the older vehicle; radical in a few respects but still adhering fairly closely to the conventional. There is good reason for believing that much more radical changes are not only possible but would be economically valuable.

To the author, this development is interesting chiefly because it demonstrates the dollar value of the research method in an old and apparently completely developed line of endeavor. Now that the door to new designs has been opened, lengthy vistas, extending far into the future and apparently filled with promise, have come into view.

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A New A-C Network Analyzer

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Introduction

WHEN POWER systems were relatively small and simple, frequently comprising only one generating station with a radial distribution system, there was little need to study the effect of a proposed addition or change on an existing system. The growth and in recent years the interconnection of power systems have brought with them an increased quality of electric service and divers new devices for maintaining that service. In a power system of the size and complexity of many of those now in operation, many of the component parts inherently have the ability to profoundly affect the successful operation of the system. Consequently, it has become necessary for engineers to study their systems much more critically and to know a great deal more about them than heretofore. Fortunately, the technical background for such critical studies has kept pace with the increase in size and complexity of power systems. However, the calculations which constitute a large part of the work of making such a critical study, when carried out by long hand methods are generally laborious—frequently, sufficiently laborious to greatly curtail the scope of the study and at times to prevent the study being made altogether.

To simplify and shorten the work of making calculations of this sort, the a-c network analyzer has been developed. It is a tool which in the hands of a competent engineer becomes a very valuable aid in analyzing the performance of systems and apparatus. Moreover, a much more complete analysis of a power system and the interrelated performance of its component parts may be obtained from the analyzer data than can be gathered from actual system data and operating reports, which must of necessity be in some degree incomplete.

The analyzer affords a quick and effective means for studying major system disturbances in order to check and correlate available field observations, to determine what probably occurred, and to compare suggested remedies. It is useful also for observing in "slow motion" the sequence of events during abnormal system operation. Periodic checks with it of normal system operation and of operating instructions frequently show important changes brought about by the shift and growth of loads. Furthermore such checks often afford explanations for unusual observed operating phenomena. The comprehensiveness of the picture secured with the help of the analyzer of all the many factors which enter into the solution of a problem and which must be accurately weighed in fashioning its solution has created a feeling among those who have used the analyzer that all changes and additions to power systems involving major expenditures could profitably be critically studied with it.

From the historical point of view some of the first attempts to study power system problems were made with miniature three-phase systems using laboratory equipment,[1] some employing rotating machines as large as 600 kva at 23,000 volts[5] for the determination of stability and power limits. A general purpose three-phase miniature a-c transmission system for the practical solution of network and transmission problems employing 3.75 kva rotating generators was constructed and extensively used in the General Electric Company.[3,4] In all of these early arrangements rotating generators of appreciable power were used. Later, however, the method of symmetrical-component analysis of unbalanced three-phase systems suggested the use of single-phase artificial representations of such systems. The representation of generators by means of static phase shifting transformers and the use of transformer equivalent circuits was described by Messrs. H. H. Spencer and H. L. Hazen[6]. By applying these principles, the MIT network analyzer[9] was built jointly by the General Electric Company and the Massachusetts Institute of Technology. Another a-c calculating board of interesting design was also built and described by the Westinghouse Electric and Manufacturing Company.[10]

Design Fundamentals

Experience gained through the operation of the earlier analyzers showed that refinements in the general usability, degree of accuracy and reduction of size, and weight are desirable.

Usability may be considered from several standpoints. For example, in setting up the network on the analyzer a suitable number of circuit units should be available to adequately represent any power system. System quantities should be easily converted into analyzer quantities and vice versa. The adjustment of analyzer circuit units should be simple and connections of the units to form a network should be capable of being made with facility. The parts of the analyzer should be so arranged that visual checks of the connections and settings of the units can be readily made. It follows that all of these things apply equally well when adjusting an already formed network to a new set of conditions.

If the measuring system is to have maximum usability it should be such that data may be obtained from the analyzer as rapidly as it can be recorded, and that desired electrical quantities such as volts, amperes, watts, vars,

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1. For all numbered references, see list at end of paper.

Figure 1. Network analyzer showing the general arrangement of cabinets

vector components of voltage and current as well as phase angles should be read directly. It must be easy to insert the measuring instruments in the network at the points desired and to read the instrument scales accurately and without eyestrain. The importance of obtaining correct data can hardly be overemphasized, as mistakes which arise either through faulty plugging and setting of units through improper reading of instruments or through fatigue, sometimes result in serious delays and unnecessary duplications of work.

A network analyzer should have a degree of accuracy at least equal to the accuracy of the constants of the systems which are to be reproduced in miniature. An even higher degree of accuracy is desirable in order that small differences in operating conditions and apparatus constants will produce the corresponding changes in associated network currents, voltages, and power flow. It is also desirable that a sufficient number of adjustable steps be provided on the circuit units that system constants may be set up with a good degree of accuracy. The instruments must have sufficiently low burdens that they will produce negligible changes in network currents and voltages. Moreover the departures of the analyzer units and instruments from their calibration should seldom be sufficiently large that correction of the measured results are necessary.

In view of the fact that the large number of circuit units generally occupy the greatest portion of the analyzer space, these units should be made small in order to reduce the analyzer size and weight. This can be achieved, as a preliminary design analysis showed, by using small network currents and voltages and by selecting an appropriate operating frequency. In this manner the power consumption is also minimized so that a small motor-generator set may be used. Furthermore, the over-all heat dissipation from the analyzer becomes small as is desired. In addition, standard high-quality low-cost switches, terminal plugs, etc., which, through years of use in radio and telephone fields have attained a high degree of durability and dependability, may be used.

The New A-C Network Analyzer

In the design of the analyzer described in this paper an effort was made to achieve all of the objectives outlined in the preceding section. In order to satisfy certain of these objectives many new developments were necessary, particularly the development of a new instrument system including amplifiers.

Before discussing in detail the essential design features and engineering problems it is perhaps well at this point to describe briefly the new analyzer recently placed in operation in the General Electric Company at Schenectady.

The general arrangement may be seen from figure 1 showing the center and one wing of the analyzer. It is assembled symmetrically with respect to the centrally located instrument and control cabinet. A circuit-connecting cabinet is situated on either side of this control cabinet and each wing is formed by four cabinets containing the adjustable circuit-element units. The distance from wing to wing is 26 feet and the depth is 11 feet. Power is supplied to the network through generator units placed in the upper part of the circuit-connecting cabinets and the instruments and control cabinet. This power is derived from a motor-generator set and phase balancer remotely located from, but controlled from the analyzer.

Each circuit unit terminates in a set of flexible cords and plugs on the connecting cabinets. By inserting these plugs in horizontally adjacent jacks of the vertical jack panel of these cabinets the circuit units may be connected together to form the desired network. The end jacks of each horizontal row of one jack panel are connected to the respective end jacks of the other jack panel, thus interconnecting them. The generator units are connected to rows of jacks located on the extreme ends of each jack panel.

Key switches are provided on the inclined panel of the instrument cabinet to connect any circuit unit or "jumper circuit" of the network to the instrument busses. Other switches for operating the instruments are provided on the vertical instrument panel so that the operator may

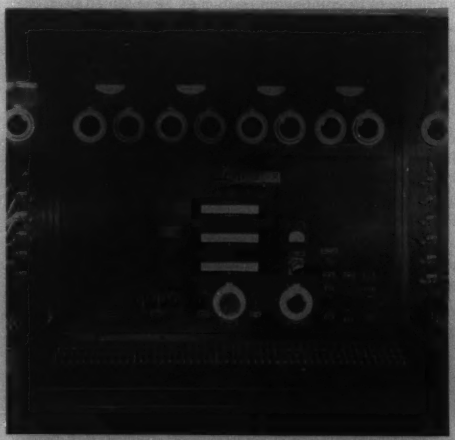

Figure 2. Central instrument and control panel showing generator units and instruments with their control switches

measure the magnitudes or vector components of voltage, current and power, and phase angles in any branch of a network without moving from in front of the instrument cabinet, a close view of which is shown in figure 2.

The master instruments consist of an ammeter, voltmeter, and wattmeter - varmeter. They have light-beam pointers in order to secure a short response time. The light beam pointers used in conjunction with eight-inch scales reduce eyestrain to a marked degree. In order that these instruments shall have very low burdens and so make an inappreciable change in the network currents, current and voltage amplifiers are used.

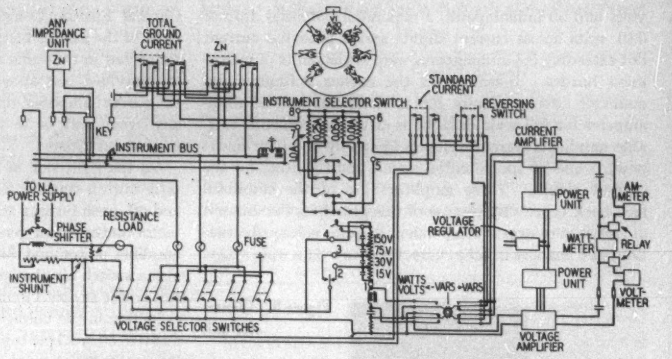

Figure 4. Schematic circuit diagram of the instrument system connections

The dials and scales of all of the analyzer circuit units and instruments are marked in per cent. With this marking the multipliers for changing system quantities into analyzer quantities and vice versa are simpler than they would be if the analyzer scales were marked in actual volts, amperes, and ohms. Furthermore, as a great many system calculations are made using percentage quantities, data for these systems may be frequently transferred directly to the analyzer. The nominal or 100 per cent voltage is 50 volts and the nominal or 100 per cent current is 50 milliamperes. Consequently 100 per cent ohms on the analyzer corresponds to 1,000 ohms.

The wiring between sections of the analyzer is carried in the base of the cabinets as may be seen from figure 3, which shows a back view of the circuit-unit cabinets. The circuit units are mounted in individual compartments and may readily be removed for inspection.

All cabinets are of the unit type and might have been arranged in any other manner than that shown in figure 1 if the configuration of the room had required it.

Figure 3. Rear view of two circuit-unit cabinets showing the wiring details

The Instrument System

One of the most important parts of the network analyzer is the master-instrument group and its controls. The master instruments, the voltmeter, the ammeter and wattmeter-varmeter, are of the "light beam" type with eight-inch scales having 150, 100, and 150 divisions respectively. The "light beam" pointer is a luminous figure on the opalescent instrument scale consisting of a thin vertical line. These instruments were constructed from modified standard instrument elements by replacing the pointers with reflecting mirrors in the usual manner. Owing to the light-beam pointers and suitable moving system springs, the time of response of these instruments is a fraction of a second. The voltmeter and ammeter are of the moving-iron-vane type and the wattmeter-varmeter is a d-c milliammeter of the permanent-magnet moving-coil type whose d-c operating current is supplied by the wattmeter proper which is a sensitive torque balancing telemeter. In this telemeter-wattmeter a null method of measurement similar to that of the photo-electric recorder was used.[16] The a-c potential coils and the current coils of the instruments are connected in series so that all master instruments indicate simultaneously.

For the nominal analyzer voltage and current of 50

volts and 50 milliamperes, a maximum potential drop of 0.01 volts across current shunts and a potential current not exceeding 0.3 milliamperes were set as limits of instrument burden. Inasmuch as the master voltmeter and ammeter circuits require 100 milliamperes and 50 milliamperes for full scale deflections of the instruments, suitable amplifiers were developed to supply the instrument power—one for the potential circuit and the other for the current circuit. These amplifiers are of the stabilized feed-back type. By the use of this principle, the amount of gain is very nearly independent of plate voltage fluctuations and changes in tube characteristics over a wide range.

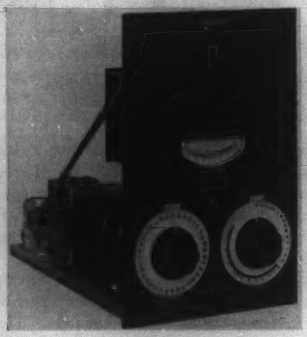

Figure 5. Generator unit

The accuracy of the amplifiers is further improved by a simple transformer-type checking circuit which automatically compares the amplifier input and output and introduces into the amplifier a voltage corresponding to any differential from the correct ratio of these two quantities, so that the amplification ratio is accurately maintained. The amplifiers have an accuracy of better than plus or minus 20 minutes in phase angle and plus or minus one-half per cent in magnitude. They are fully described in a paper by H. A. Thompson.[15]

A complete schematic circuit diagram showing the connections of the instruments, amplifiers, and the instrument switches is shown in figure 4. Referring to figure 2, the instrument-scale-selector switch, having seven positions corresponding to the most common voltage and current scales used, is installed just below the master instruments. By means of an auxiliary switch located on the right of the scale selector switch two additional low-voltage ranges are provided. On the left of the scale selector switch there are installed the watt-varmeter switch and the current-reversing switch.

By means of voltage switches, which are in the bottom row to the left of the master instruments, the voltages across any circuit unit or from either side of a circuit unit to ground, or from either side of a circuit unit to another point in the network, may be connected to the voltage amplifier. In addition, for measuring vector components of current, a reference voltage obtained from the instrument Selsyn (Selsyn is a registered trademark of the General Electric Company), which is below and to the right of the master instruments on the panel, may also be connected to the same amplifier. Three current switches are provided just above the voltage switches to connect the current amplifier through shunts to the ground bus or any circuit unit, or to the reference current circuit of the instrument Selsyn.

On the right side of the panel there are the start-stop push-button stations for the motor-generator set, the on-and-off push-button stations for the power-supply contactor on the motor-generator set control panel and for the amplifier-power and instrument-light switch. There is also a switch for changing taps on the autotransformer in the power supply circuit in order to obtain a convenient reduction in the voltages of all generator units simultaneously to 50 or 25 per cent voltage when faults are applied to the network. A miniature type voltmeter is supplied to indicate the analyzer supply voltage. A rheostat is provided to adjust the voltage held by the voltage regulator associated with the motor-generator set. To the left of the master instruments a second rheostat is provided to adjust the voltage and current of the instrument Selsyn.

The potential shunt or voltage divider and the current shunts for the master instruments shown in figure 4 are mounted in the scale-selector-switch housing. Because of the high impedance of the voltage divider, the capacity coupling to ground and to adjacent electrical circuits of the divider elements introduces currents which cause phase-angle shifts. It is necessary to have very close adjustment of phase angles to measure power at low power factors with the degree of accuracy sometimes required in stability studies when large machines are involved. In order to control these stray-capacity effects, adjustable trimmer capacitors have been connected across the resistance parts of the divider to equalize the phase-angle shifts on all taps. The effects of the capacity to ground have been made inappreciable by proper shielding of the divider, shunt leads and switches. Inasmuch as the voltage divider now has a permanent and constant leading phase-angle shift the current shunts have been wound inductively and made adjustable in inductance in order that the voltage drop of each shunt will have the proper phase position with respect to the input voltage of the potential amplifier for correct measurement of power at power factors approaching zero.

In the diagram of figure 4 only a typical circuit unit and corresponding key switch is shown; there are 300 key switches in the analyzer, one for each circuit.

The over-all accuracy of the master voltmeter and ammeter systems is within plus or minus 0.5 per cent of full

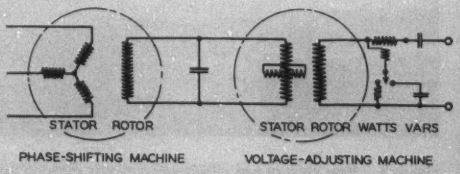

Figure 6. Schematic circuit diagram of generator unit

scale. The wattmeter-varmeter has the same accuracy when the phase angle between the current and voltage is not large. For very low power-factor measurements the most frequently used instrument connection has been carefully adjusted as described above to give accurate measurements of watts and vars at phase angles between the voltage and current approaching 90 degrees. For all other instrument connections there is a maximum instrument system phase angle displacement of the order of one degree.

The Analyzer Generator Units

Referring to figure 1, 12 adjustable single-phase power-source or generator units are installed in suitable compartments located at the top of the two plugging cabinets and the central instrument cabinet. These units are completely self-contained and may be inserted or removed from their compartments from the front. A photograph of one of these units is shown in figure 5.

Each generator unit consists of two power Selsyns, one having a three-phase stator and single-phase rotor for phase-angle control, the other having a two-phase stator and a single-phase rotor for voltage control. A schematic connection diagram is shown in figure 6. The three-phase stator winding of the phase shifting Selsyn is excited at 220 volts and 480 cycles through an autotransformer from the main power supply, the motor-generator set. The phase angle of the induced voltage in the single-phase rotor winding depends on the rotor angle. The rotor-output voltage is applied to one of the quarter-phase stator windings of the voltage-adjusting Selsyn. By turning the single-phase rotor of this machine the voltage may be varied from zero to a maximum at an essentially constant phase angle. As shown in the circuit diagram of figure 6, capacitors were used to compensate for magnetizing current and the equivalent single-phase reactance of the unit.

The full-load (100 per cent current) voltage regulation of the unit is approximately 2 per cent at unity power factor and essentially zero at zero power factor. The phase-angle shift for a corresponding change of current at zero power factor is approximately one degree at zero power factor and approximately zero at unity power factor. Because of this close regulation, a calibrated voltage dial was supplied with the voltage regulator instead of a voltmeter. By means of a gear transmission, the 90-degree mechanical rotor angle, from zero to full voltage, is magnified to an angle of approximately 300 degrees on the voltage dial, making the setting of the voltage more convenient.

The only direct-reading instrument mounted on the panel of this unit is a wattmeter-varmeter for measuring or adjusting the active and reactive voltampere output. This instrument has 150 per cent and 300 per cent voltage ranges and 100 per cent and 400 per cent current ranges. Switches are provided for changing scale multipliers and for short-circuiting the current coil when the generator-unit current exceeds 400 per cent. A switch is also supplied to disconnect the generator unit from the power supply.

Table I. Voltage-Wave-Shape Analysis of Analyzer Power Sources

Harmonic	Frequency (Cycles)	Voltage Components					
		Volts	Per Cent	Volts	Per Cent	Volts	Per Cent
At no load							
1	480	50.00	100.00	100.00	100.00	125.00	100.00
3	1440	0.13	0.26	0.5	0.5	0.66	0.525
5	2400	0.65	1.3	1.26	1.26	1.53	1.22
7	3360	0.028	0.056	0.057	0.057	0.068	0.054
With 0.25 ampere (500 per cent) at 70 per cent power factor							
1	480	50.00	100.00			125.00	100.00
3	1440	0.11	0.22			0.73	0.58
5	2400	0.62	1.24			1.68	1.34
7	3360	0.0275	0.055			0.066	0.053

In the design of the power supply motor-generator set and also of the analyzer generator units themselves, care was exercised to keep harmonics in the voltage to a minimum. With the complete analyzer equipment installed a voltage-wave-shape analysis was made at the output terminals of the generator units. The results are shown in table I.

The fifth-harmonic voltage is the largest but it does not exceed 1.4 per cent. Thus the analyzer generator-unit output voltage is very nearly sinusoidal.

The Circuit Units

For the representation of power systems by means of artificial miniature equivalent circuits there are generally used, in addition to generator units, adjustable resistors, reactors, capacitors, autotransformers, and mutual reactors. These may be combined into groups to form network branches. In the new analyzer there are five different types of circuit units as follows:

(*a*). Line-impedance units. These consist of adjustable resistors and reactors connected in series and are intended for representing lines or other circuits of relatively small impedance.

(*b*). Load-impedance units. These units also consist of adjustable resistors and reactors which may be connected either in series or in parallel. They differ from the line-impedance units in that their impedances are much higher.

(*c*). Capacitor units. The adjustable capacitors of these units are used to represent line capacity, and frequently to represent synchronous condensers as well as negative reactance such as occur in equivalent transformer circuits.

(*d*). Autotransformer units. The autotransformers are used to step up or down the voltage at points in the network.

(*e*). Mutual-transformer units. By means of these units magnetic coupling between circuits may be simulated. They are 1:1 ratio transformers. The desired degree of mutual coupling is obtained by connecting across the secondary a suitable impedance.

All units, with the exception of the last one which is not adjustable in itself, are mounted on individual 7- by 16-inch metal bases with calibrated front panels attached. These mounted units fit interchangeably into the compartments of the circuit-unit cabinets. The mutual-transformer units are mounted on racks back of the connection cabinet jack panels. Figure 7 shows a photograph of a line-impedance unit and a load-impedance unit while figure 8 shows a capacitor-unit and an autotransformer

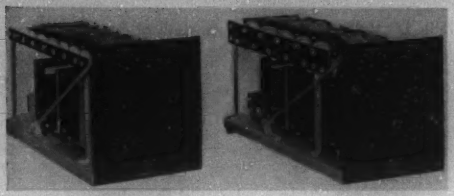

Figure 7. Line and load-impedance units

unit. An individual mutual-reactor unit is shown in figure 9.

In determining the proper number and the kind of units for the analyzer a great many systems were inspected and their constants tabulated. Studies which have been made on other analyzers were thoroughly reviewed. The constants of synchronous machines, transformers, and the like, were examined in order that the analyzer units would cover adequately the necessary ranges of impedance and fineness of steps. The following table shows the

Table II. Number and Range of Circuit Units

Units	Number	Per Cent Range	Steps
Line-impedance units (series $R + jX$)	150	R 0–51 per cent	Continuous
		X 0–81 per cent	0.2 per cent
Load-impedance units	50	R 0–1,610 per cent	Continuous
(series or parallel $R + jX$)		X 0–1,605 per cent	5 per cent
Capacitor units (susceptance)	30	0–100 per cent	1 per cent
Autotransformer units	12	* 15 per cent *	1 per cent
Mutual-reactor units	15		

* Values expressed in per cent of primary voltage.

number and range of circuit units in the new network analyzer.

The resistance and reactance part of each line-impedance unit and load-impedance unit is individually rated at a maximum of 62.5 volts (125 per cent nominal voltage) or 250 milliamperes (500 per cent nominal current) whichever is the limiting factor. Each capacitor of the capacitor units is rated at a maximum of 62.5 volts (125 per cent nominal voltage). The tapped resistances and capacitors have an accuracy of plus or minus one per cent on all taps. Small variable resistors have an accuracy of plus or minus three per cent. All reactors have an accuracy of plus or minus one per cent at a specified current and a change of reactance less than plus or minus two per cent over the full current range at any setting.

An ideal reactor should have a very small R/X ratio. However, there are obviously practical limits of R/X ratio below which a reactor tends to become unduly expensive and large. Thus the values of R/X given in table III of the circuit-unit reactors represent a compromise between reasonable cost and an acceptable R/X ratio.

In the design of the reactors, autotransformers, and mutual-reactance units, low losses and high permeability at the low flux densitites were desirable; consequently, nickel-iron-alloy magnetic cores were generally used.

The autotransformers are rated at 62.5 volts (125 per cent) and 250 milliamperes (500 per cent). The taps are accurate to plus or minus one per cent of the dial setting. The series reactance of these transformers is compensated with suitable series capacitors.

The mutual-transformer units are rated 62.5 volts (125 per cent) and 250 milliamperes (500 per cent). The two windings of this unit, a 1:1 ratio transformer, are wound together so that minimum leakage reactance is obtained. The relatively large capacity coupling resulting from the close spacing of the wires is compensated by means of a small reactor connected from one winding to the other.

The Motor-Generator Set

The motor-generator supplies three-phase, 480-cycle power at 440 volts through an autotransformer to the 12

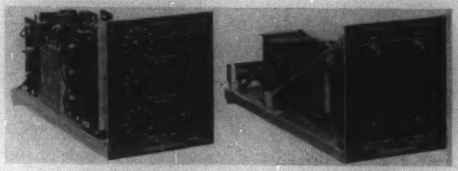

Figure 8. Capacitor and autotransformer units

analyzer generator units. Because of the low analyzer circuit voltage and currents used, the maximum 480-cycle input to the entire analyzer is less than 5 kva. The single-phase component is less than one kva.

In order to maintain substantially balanced voltages at the terminals of the three-phase generator with a single-phase load component, a phase balancer is connected in parallel with it. The phase balancer is directly coupled to the generator and rotates at synchronous speed. In addition to its voltage balancing action, the phase balancer absorbs a good deal of the small residual harmonic content of the voltage of the sine-wave generator. The phase balancer magnetizing current is compensated by means of suitable capacitors.

The complete motor-generator set assembly consists of

Table III. Typical R/X Ratios of Circuit-Unit Reactors

Circuit Unit	Reactance Setting (Per Cent)	R/X Ratio (Per Cent)
Line-impedance unit	0.2	.8
	1.0	5.5
	10.0	3.5
	70.0	3.0
Load-impedance unit	5	5.0
	10	4.5
	100	3.5
	1,500	3.0

four machines, a 60-cycle driving motor, a 480-cycle alternator, a phase balancer, and an exciter, all directly coupled and mounted on a 20-inch-by-7-foot base.

In view of the small amount of 440-volt, 480-cycle power to be transmitted, the motor-generator set may readily be remotely installed from the analyzer. In the General Electric installation the distance is of the order of 200 feet and considerably larger distances are quite feasible.

Conclusions

The operation of the analyzer since it was completed has shown that the design has achieved the high degree of facility and speed of operation which was expected with a resultant saving roughly the equivalent of one operator. When the occasion arises the analyzer may be operated conveniently by a single operator. The over-all accuracy and accuracy of the component parts has been within the limits for which the equipment was designed.

Figure 9. Mutual-reactance unit with compensating reactor

The following distinctive design features have contributed to the efficient analyzer performance:

1. The instruments and all selector-key switches are centrally arranged, so that the operator may take conveniently the desired readings of the network quantities from one position in front of the instrument cabinet without assistance.

2. The concentration of the circuit unit connecting equipment in two cabinets facilitates the work of connecting the circuit units to form the network to be studied. In addition, the amount of transfer plugging, frequently a source of error, is materially reduced. With this arrangement the network busses may be formed on the plugging panels in the same relative positions which they have on the network diagram, affording easy checks of all connections.

3. The accurate light-beam-type instruments have a very short time of response and serve to measure voltage, current, watts, (vars) reactive voltamperes, and vector components of voltage and current with a minimum of eyestrain. In the measurement of these vector components and for reading phase angles an instrument Selsyn is used.

4. The instrument burdens have been reduced to very low values by the use of precision amplifiers of the stabilized type. Thus the introduction of the instruments in the network has a negligible effect on the existing distribution of voltage and current, resulting in a degree of accuracy of the measurements which precludes the need for correction of the measured results.

5. The close electrical tolerances to which all the component parts of the analyzer have been held, have resulted in the practical elimination of the use of correction tables for adjusting the network impedances to the values desired for the representation of the power network.

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The Properties of Three-Phase Systems Deduced With the Aid of Matrices

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ANY MATHEMATICAL process, even though fully developed in theoretical form, takes on more meaning, and thereby becomes more useful, if it is applied to familiar concepts. If in this application certain conclusions can be reached with ease which ordinarily are reached with difficulty, the utility of the mathematical process is still more conclusively demonstrated.

Three-phase circuits are very generally used. The simpler properties of such circuits have been considered, and have been taught in colleges for many years. There are, however, certain important properties of these systems, deduced in the following, which are not as widely known as they should be. The reason for this fact is simply that ordinarily the equations required to deduce these results get so cumbersome as the work progresses that the details hide the general properties of the system. Matrices are extremely effective in clearing away the complication of detail thus leaving the expressions for the general properties of the system more evident.

A further advantage of matrix nomenclature is that even to a beginner in the study of polyphase systems, after having mastered the matrix treatment of three-phase systems, the method of extending the details of the matrices to any other polyphase system will be evident.

The following treatment of three-phase systems shows the power of matrices, not only in simplifying the statement of the properties of circuits in general, but in determining the detailed properties of particular circuits. The method of manipulating matrices and of reaching certain conclusions from them is shown.

Preliminary

A nomenclature, convenient for all occasions when complex numbers, real numbers, vectors, and matrices are all used in the same discussion, is not easily established. The writer has found through his own investigations and through presenting the material to students that the following symbolism is simple and convenient: a matrix will be represented by the script symbols

$\mathfrak{A}, \mathfrak{B}, \mathfrak{Z}, \mathfrak{I}, \mathfrak{E}$, etc.,

a complex number or vector in the usual complex notation by

V, I, y, z, etc.,

and a scalar or real number by the absolute value as

$|V|, |I|, |y|, |z|$, etc.

This symbolism will be used in what follows.

The properties of matrices as given in the paper by Pipes[1] will be assumed, in as far as they are needed, in what follows. In addition, and in keeping with the nomenclature to be used in this discussion, the unit matrix will be designated as

$$\mathfrak{A}_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \tag{1}$$

Other unit matrices which will be used below, formed by shifting the last column successively to the first column position, are

$$\mathfrak{A}_2 = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix} \text{ and } \mathfrak{A}_3 = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \tag{2}$$

The following matrices will also be useful:

$$\mathfrak{A}_{12} = \mathfrak{A}_1 - \mathfrak{A}_2 \text{ and } \mathfrak{A}_{13} = \mathfrak{A}_1 - \mathfrak{A}_3 \tag{3}$$

Note that the matrices given by equation 3 are singular.

Three-Phase Delta Connection

(*a*) *General:* In matrix notation the voltage equations in terms of the cyclic currents for figure 1—assuming no mutual inductance or capacitance—are

$$\mathfrak{E} = \mathfrak{Z}\mathfrak{I} \tag{4}$$

where

$$\mathfrak{E} = (E_{12}, E_{23}, E_{31}, 0) \tag{5}$$

$$\mathfrak{I} = (I_{12}, I_{23}, I_{31}, I_4) \tag{6}$$

and

$$\mathfrak{Z} = \begin{pmatrix} z_{12}+z_{1B}+ & -z_{1B} & -z_{A1} & -z_{AB} \\ z_{BA}+z_{A1} & z_{23}+z_{2C}+ & -z_{2C} & -z_{BC} \\ -z_{1B} & z_{CB}+z_{B2} & z_{31}+z_{1A}+ & -z_{AC} \\ -z_{A1} & -z_{2C} & z_{AC}+z_{3C} & z_{AB}+ \\ -z_{AB} & -z_{BC} & -z_{AC} & z_{BC}+z_{CA} \end{pmatrix} \tag{7}$$

The current and voltage matrices are to be considered as one columned, but are written as in equations 5 and 6 as a matter of convenience.

Further, since the impedance matrix is not singular,

$$\mathfrak{I} = \mathfrak{Y}\mathfrak{E}$$

where the admittance matrix is the inverse of the impedance matrix of 7.

The phase currents at the generator are

$$\mathfrak{I}_{yg} = (I_{12}, I_{23}, I_{31}) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix} \mathfrak{I} = \mathfrak{T}_{yg} \triangle \mathfrak{I} \tag{8}$$

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1. For numbered reference, see end of paper.

and the phase currents at the load are

$$\mathfrak{I}_{pl} = (I_{BA}, I_{CB}, I_{AC}) = \begin{pmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 1 & -1 \end{pmatrix} \mathfrak{I} = \mathfrak{T}_{pl}{}^{\Delta}\,\mathfrak{I} \tag{9}$$

The line currents are

$$\mathfrak{I}_L = (I_{A1}, I_{B2}, I_{C3}) = \mathfrak{U}_{11}\mathfrak{I}_{pg} = \mathfrak{U}_{11}\mathfrak{I}_{pl} = \mathfrak{U}_{11}\mathfrak{T}_{pg}{}^{\Delta}\mathfrak{I} = \mathfrak{U}_{11}\mathfrak{T}_{pl}{}^{\Delta}\mathfrak{I} \tag{10}$$

Note, as is evident from figure 1 and equations 8 and 9, that $\mathfrak{I}_{pg} \neq \mathfrak{I}_{pl}$ even though equation 10 at first glance makes them appear so. The fact that the transformation matrix $\mathfrak{U}_{11}$ is singular makes this relation possible. Note

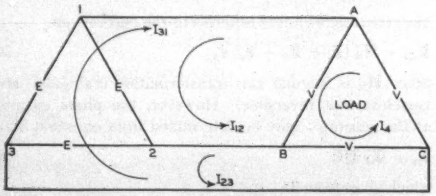

Figure 1. Three-phase delta connection

further that $\mathfrak{I}_{pg}$ or $\mathfrak{I}_{pl}$ *cannot* be determined from $\mathfrak{I}_L$ since $\mathfrak{U}_{11}$ is singular, thus pointing out a fact which is not immediately evident from the equations themselves.

The line and phase voltages at the generator are

$$\mathfrak{E}_{Lg} = \mathfrak{E}_{pg} = \mathfrak{T}_{pg}{}^{\Delta}\,\mathfrak{E} = (E_{12}, E_{23}, E_{31}) \tag{11}$$

and the terminal voltages of the generator, in terms of the voltage drops of line and load, are

$$\mathfrak{V}_{pg} = \mathfrak{E}_{pg} - \mathfrak{V}_{ig} = \mathfrak{V}_{pl} + \mathfrak{U}_{11}\mathfrak{V}_L \tag{12}$$

where the load and line drops at the generator terminals are

$$\mathfrak{V}_{pg} = (V_{31}, V_{12}, V_{23}) \tag{13}$$

the internal generator drops are

$$\mathfrak{V}_{ig} = \begin{pmatrix} z_{12} & 0 & 0 \\ 0 & z_{23} & 0 \\ 0 & 0 & z_{31} \end{pmatrix} \mathfrak{I}_{pg} = \mathfrak{Z}_g\,\mathfrak{I}_{pg} \tag{14}$$

the line drops are

$$\mathfrak{V}_L = \begin{pmatrix} z_{A1} & 0 & 0 \\ 0 & z_{B2} & 0 \\ 0 & 0 & z_{C3} \end{pmatrix} \mathfrak{I}_L = \mathfrak{Z}_L\,\mathfrak{I}_L \tag{15}$$

and the phase drops at the load are

$$\mathfrak{V}_{pl} = \begin{pmatrix} z_{AB} & 0 & 0 \\ 0 & z_{BC} & 0 \\ 0 & 0 & z_{CA} \end{pmatrix} \mathfrak{I}_{pl} = \mathfrak{Z}_l\mathfrak{I}_{pl} \tag{16}$$

Other relations may be readily set up to handle any particular problem. Some special cases of interest are given in the following.

(*b*) *Balanced Voltages and Unbalanced Load Impedances.* In order to simplify the expressions and still retain enough of the circuit for present purposes, assume that all impedances of figure 1 are zero except the three load impedances. Then since the voltages are assumed as balanced—*acb* phase sequence—

$$\mathfrak{V}_{pl} = V_{BA}\,(1, a, a^2) \tag{17}$$

where

$$a = \epsilon^{j\frac{2\pi}{n}} = \epsilon^{j\frac{2\pi}{3}} = \epsilon^{j120}$$

Also from equations 10 and 16

$$\mathfrak{I}_L = \mathfrak{U}_{11}\mathfrak{I}_{pl} = \mathfrak{U}_{11}\mathfrak{Y}_l\mathfrak{V}_{pl} \tag{18}$$

But since

$$\mathfrak{Y}_l = \begin{pmatrix} \frac{1}{z_{AB}} & 0 & 0 \\ 0 & \frac{1}{z_{BC}} & 0 \\ 0 & 0 & \frac{1}{z_{CA}} \end{pmatrix} = \begin{pmatrix} y_{AB} & 0 & 0 \\ 0 & y_{BC} & 0 \\ 0 & 0 & y_{CA} \end{pmatrix}$$

equations 17 and 18 give

$$\mathfrak{I}_L = \begin{pmatrix} y_{AB} & 0 & -y_{CA} \\ -y_{AB} & y_{BC} & 0 \\ 0 & -y_{BC} & y_{CA} \end{pmatrix} V_{BA}\,(1, a, a^2)$$

which multiplied out gives

$$\mathfrak{I}_L = V_{BA}\,(y_{AB} - a^2 y_{CA},\ -y_{AB} + a y_{BC},\ -a y_{BC} + a^2 y_{CA}) \tag{19}$$

But if the balanced voltage phase-sequence is changed to the *abc* sequence

$$\mathfrak{V}_{pl} = V_{BA}\,(1, a^2, a),$$

and

$$\mathfrak{I}_L = V_{BA}\,(y_{AB} - a y_{CA},\ -y_{AB} + a^2 y_{BC},\ -a^2 y_{BC} + a y_{CA}) \tag{20}$$

Examining these two relations—19 and 20—makes it evident that, for any set of load impedances such that their phase angles, or the ratio x/r, is the same for all three impedances, the *magnitude of the line currents will not change* under a change in phase sequence of voltage; and that for any other impedance relation the line currents will change in magnitude with a change in the phase sequence of the voltages.

(*c*) *Unbalanced Voltages and Balanced Impedances.* Considering load impedances only, evidently

$$\mathfrak{Y}_l = y\mathfrak{U}_1 \tag{21}$$

Further, if n' is located at the center of gravity of the load voltage triangle, and if

$$\mathfrak{V}_{N'} = (V_{N'A}, V_{N'B}, V_{N'C}) \tag{22}$$

then

$$\mathfrak{V}_{pl} = (V_{BA}, V_{CB}, V_{AC}) = \mathfrak{U}_{12}\,\mathfrak{V}_{N'} \tag{23}$$

But from 18, 21, and 23

$$\mathfrak{I}_L = \mathfrak{U}_{11}\,y\,\mathfrak{U}_1\,\mathfrak{U}_{12}\,\mathfrak{V}_{N'} = y\mathfrak{U}_{12}\,\mathfrak{U}_{12}\,\mathfrak{V}_{N'} \tag{24}$$

which gives

$$\mathfrak{I}_L = y \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \mathfrak{V}_{N'} = 3y\,\mathfrak{V}_{N'} \tag{25}$$

This relation shows immediately that the line currents are associated with the voltages to the center of gravity of the

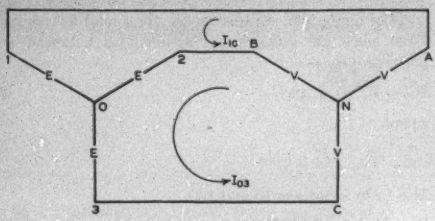

Figure 2. Three-phase wye connection

voltage triangle by the phase angle of the load impedances. Also note that the voltages to the center of gravity may be determined from

$$\mathfrak{V}_{N'} = \frac{1}{3y}\mathfrak{I}_L \tag{26}$$

(*d*) *Balanced Voltages and Balanced Impedances.* Once more considering the load only—*acb* phase sequence—

$$\mathfrak{I}_{pl} = I_{BA}(1, a, a^2)$$

$$\mathfrak{I}_L = \mathfrak{U}_{13}\mathfrak{I}_{pl} = I_{BA}\mathfrak{U}_{13}(1, a, a^2)$$

$$\mathfrak{I}_L = \sqrt{3}\, e^{j30}\mathfrak{I}_{pl} \tag{27}$$

Also since the relation between line and phase currents is now simply a complex number rather than a singular matrix

$$\mathfrak{I}_{pl} = \frac{e^{-j30}}{\sqrt{3}}\mathfrak{I}_L \tag{28}$$

Three-Phase Wye Connection

(*a*) *General.* The voltage equations in terms of cyclic currents for figure 2—assuming no mutual inductance or capacitance—are, in matrix form,

$$\mathfrak{E} = \mathfrak{Z}\mathfrak{I} \tag{29}$$

where

$$\mathfrak{E} = (E_{12}, E_{23}) \tag{30}$$

$$\mathfrak{I} = (I_{10}, I_{03}) \tag{31}$$

and

$$\mathfrak{Z} = \begin{pmatrix} z_{10}+z_{20}+z_{2B}+z_{BN}+z_{NA}+z_{A1} & -z_{02}-z_{2B}-z_{BN} \\ -z_{02}-z_{2B}-z_{BN} & z_{02}+z_{03}+z_{3C}+z_{CN}+z_{NB}+z_{2B} \end{pmatrix} \tag{32}$$

Of course, since $\mathfrak{Z}$ is nonsingular

$$\mathfrak{I} = \mathfrak{Y}\mathfrak{E}$$

The line currents of the wye system are

$$\mathfrak{I}_L = (I_{A1}, I_{B2}, I_{C3}) = \mathfrak{I}_{pg} = \mathfrak{I}_{pl} = \begin{pmatrix} 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{pmatrix}\mathfrak{I} = \mathfrak{T}_y\mathfrak{I} \tag{33}$$

The voltages are

$$\mathfrak{E}_{Lg} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \\ -1 & -1 \end{pmatrix}\mathfrak{E} \text{ and } \mathfrak{E} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}\mathfrak{E}_{Lg} \tag{34}$$

and in terms of phase voltages

$$\mathfrak{E}_{Lg} = \mathfrak{U}_{12}\mathfrak{E}_{pg}$$

Also

$$\mathfrak{E} = \begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \end{pmatrix}\mathfrak{E}_{pg} = \mathfrak{T}_{yt}\mathfrak{E}_{pg} \tag{35}$$

The subscript t will be used to denote the transpose of a matrix. The singular transformation matrices indicate that the generator phase voltages cannot be determined from $\mathfrak{E}$ or from the generator line voltages.

If the impedances of the system are written as diagonal matrices

$$\mathfrak{Z}_l = \begin{pmatrix} z_{AN} & 0 & 0 \\ 0 & z_{BN} & 0 \\ 0 & 0 & z_{CN} \end{pmatrix} \quad \mathfrak{Z}_L = \begin{pmatrix} z_{A1} & 0 & 0 \\ 0 & z_{B2} & 0 \\ 0 & 0 & z_{C3} \end{pmatrix} \quad \mathfrak{Z}_g = \begin{pmatrix} z_{01} & 0 & 0 \\ 0 & z_{02} & 0 \\ 0 & 0 & z_{03} \end{pmatrix} \tag{36}$$

the generator voltages in terms of the currents are

$$\mathfrak{E}_{Lg} = \mathfrak{U}_{12}(\mathfrak{Z}_l + \mathfrak{Z}_L + \mathfrak{Z}_g)\mathfrak{I}_{pg} \tag{37}$$

Since $\mathfrak{U}_{12}$ is singular this transformation is singular, and, therefore, not reversible. However, the phase currents at the generator may be determined from equation 33 as

$$\mathfrak{I}_{pg} = \mathfrak{T}_y\mathfrak{Y}\mathfrak{E} \tag{38}$$

which gives from 34

$$\mathfrak{I}_{pg} = \begin{pmatrix} 1 & 0 \\ -1 & 1 \\ 0 & -1 \end{pmatrix}\mathfrak{Y}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}\mathfrak{E}_{Lg}$$

Also from 38 and 35

$$\mathfrak{I}_{pg} = \mathfrak{T}_y\mathfrak{Y}\mathfrak{T}_{yt}\mathfrak{E}_{pg} \tag{39}$$

This equation cannot be used to determine $\mathfrak{E}_{pg}$ in terms of $\mathfrak{I}_{pg}$ because of the singularity of the transformation. Further investigation will show that no relation can be found for $\mathfrak{E}_{pg}$ in terms of $\mathfrak{I}_{pg}$ and the circuit impedances or admittances; i. e., given a set of wye-connected impedances and the line currents, the phase generator voltages of the source cannot be computed. There is an infinite set of these phase voltages which will satisfy the system.

(*b*) *Balanced Voltages and Unbalanced Load Impedances.* Using 39 and the fact that

$$\mathfrak{E}_{pg} = E_{10}(1, a, a^2)$$

for the 132 sequence, a relation corresponding to the delta circuit relation may be deduced; namely, that if the three-phase impedances have the same ratio x/r, a change of phase sequence will not affect the current magnitudes.

(*c*) *Unbalanced Voltages and Balanced Load Impedances.* Assuming all but load impedances as negligible, equation 32 reduces to

$$\mathfrak{Z} = \begin{pmatrix} 2z & -z \\ -z & 2z \end{pmatrix} = z\begin{pmatrix} 2 & -1 \\ -1 & 2 \end{pmatrix} \text{ and}$$

$$\mathfrak{Y} = \frac{1}{3}\begin{pmatrix} 2y & y \\ y & 2y \end{pmatrix} = \frac{y}{3}\begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix}$$

Then from 39

$$\mathfrak{I}_L = \mathfrak{I}_{pg} = \frac{y}{3}\begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix}\mathfrak{E}_{pg} \tag{40}$$

If $E_{10} + E_{20} + E_{30} = 0$ this relation becomes

$$\mathfrak{I}_L = \mathfrak{I}_{pg} = y\mathfrak{E}_{pg}$$

A further property of this system may be deduced as follows: the phase drops at the load are

$$\mathfrak{V}_{pl} = \mathfrak{Z}_l \mathfrak{I}_{pg} = z \mathfrak{U} \mathfrak{I}_{pg} = z \mathfrak{I}_{pg} \tag{41}$$

Further, in terms of the voltages to the center of gravity of the generator voltage triangle,

$$\mathfrak{E} = \mathfrak{T}_{yt} \mathfrak{E}_{pg}' = \mathfrak{T}_{yt} (E_{10}', E_{20}', E_{30}') \tag{42}$$

and from 38 and 42

$$\mathfrak{I}_{pg} = \mathfrak{T}_y \mathfrak{Y} \mathfrak{T}_{yt} \mathfrak{E}_{pg}' = \frac{1}{3} y \mathfrak{T}_y \begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix} \mathfrak{T}_{yt} \mathfrak{E}_{pg}' \tag{43}$$

Hence from 41 and 43

$$\mathfrak{V}_{pl} = \frac{1}{3} \mathfrak{T}_y \begin{pmatrix} 2 & 1 \\ 1 & 2 \end{pmatrix} \mathfrak{T}_{yt} \mathfrak{E}_{pg}' = \frac{1}{3} \begin{pmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{pmatrix} \mathfrak{E}_{pg}' \tag{44}$$

But since $E_{10}' + E_{20}' + E_{30}' = 0$

$$\mathfrak{V}_{pl} = \mathfrak{E}_{pg}' \tag{45}$$

which shows that the neutral or common point of the load voltages is at the center of gravity of the line voltage triangle.

(*d*) *Balanced Voltages and Impedances.* The voltages are—sequence *acb*—

$$\mathfrak{V}_L = \mathfrak{U}_{12} \mathfrak{V}_{pl} = \mathfrak{U}_{12} V_{NA} (1, a, a^2)$$
$$\mathfrak{V}_L = \sqrt{3}\, \epsilon^{-j30} \mathfrak{V}_{pl} \tag{46}$$

Also the phase voltages may for this special case be determined from the line voltages as

$$\mathfrak{V}_{pl} = \frac{\epsilon^{j30}}{\sqrt{3}} \mathfrak{V}_L \tag{47}$$

Further from 39 and the conditions here being considered

$$\mathfrak{I}_{pg} = y \mathfrak{E}_{pg} = y \mathfrak{V}_{pl} \tag{48}$$

Reference

1. Matrices in Engineering, Louis A. Pipes. Electrical Engineering, September 1937, pages 1177–90.

A System of Electric Remote-Control Accounting

By L. F. WOODRUFF
MEMBER AIEE

THE ACCOUNTING system which will be outlined in this paper will be discussed mainly in its application to a department store. However, it will not require any great stretch of the imagination to visualize the application of the same system and devices to other fields, including factory production control and pay rolls, public-utility accounts receivable, and others.

The Punched-Card Method

The punched-card method of accounting by automatic machinery has had a steady growth since its use in the United States census tabulation of 1890. At the present time the method is used in the great majority of large corporations, and literally *billions* of cards are used every year in this country alone.

In its simplest elements, the method involves the preparation of cards through which are punched holes in certain coded positions to represent numbers, or, more rarely, letters of the alphabet. The cards after preparation are stacked in hoppers of automatic machines, through which they are fed one by one, and the coded numbers picked up by electrical or mechanical sensing devices. These sensing devices in turn control adding units or other devices which do the actual accounting. There are machines for sorting, adding, subtracting, and multiplying, and these have many kinds of automatic controls which it would be out of place to describe in detail here.

The system of remote-control accounting which it is proposed to describe is not a complete system in itself, but has been designed as an aid and adjunct to extend the field of economical application of the punched-card method.

The Economical Application of the Punched-Card Method

The punched-card method is usually found to be economical of application where large masses of numerical data must be handled accurately and totaled in numerous groupings. Small quantities of data may be handled well on the machines, but the costs of handling on punched cards are much more favorable if there is enough work to keep at least a full set of machines busy continuously. The speeds and capacities of the machines are so great (400 cards per minute for the sorters, 150 per minute for the tabulators) that large masses of data are required to keep the machines usefully employed.

It should be clear also that when the cards have once been prepared (i.e., punched and checked) it is a relatively easy matter to run off a new set of statistics from them by sorting them automatically into new groupings, and tabulating them in these groupings. The more groupings into which it is desired to tabulate and totalize the information, the smaller the fraction of the card cost and punching cost which should properly be allocated against each tabulation, and therefore the method shows up most favorably when there are numerous groupings to be handled.

The census, which was the first application of the punched-card method, still stands out as the ideal type of job in its great mass of data and numerous segregations desired.

It should not be inferred that where the number of segregations is small, the punched-card method is undesirable, because other factors than direct cost, such as speed and precision, may be controlling factors. Other things being equal, however, it is unquestionably true that the most favorable applications are as has been stated. By way of illustration we may note that some of the most successful, widely adopted, and long continued applications have been in the fields of insurance, chain groceries, factory production control, and payroll. In insurance, the cards are used for many forms of actuarial analysis as well as for handling the specific dollar accounting of the policy holders individually. In chain grocery warehousing, a single card can be used in turn as an on-order record, for making a tally list for checking merchandise received, as a record in a perpetual inventory, as an order to ship to an individual retail store, and as a billing medium to that store. Thereafter, with additional data of store identification and date of shipment punched in, it is available with other cards to furnish various analyses of store performance, turnover of merchandise, profit by manufacturer, etc., etc. It would perhaps become tedious to describe in a similar vein the various uses to which a punched card is put in the other applications which have been mentioned.

There are of course accounting problems which involve so few segregations of data that they are not suitable for solution by the punched-card method, and there are others in which the advantages and disadvantages neutralize; and this in spite of a large volume of data.

In one or the other of these last two classifications lie most of the phases of accounting and control in large department stores. There have been dozens of punched-card installations in department stores, but many of these after thorough trial have been discontinued. It is apparent then that the executives in this large field are receptive to the idea, and that there are many advantages in its appli-

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1. For all numbered references, see list at end of paper.

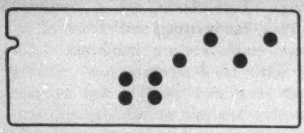


Figure 1. Punched token

cation, but these are just about offset by the disadvantages, which include the costs. Since this situation seemed favorable to the application of an auxiliary development, and further since the accounting problems of department stores are more standardized than, say, those of manufacturing plants, while yet offering comparable volume, the department store was selected as the field of the first experimental installation of remote-control accounting.

The magnitude of the department store accounting problem can be appreciated from a few statistics. There are approximately 300 department stores and departmentized specialty stores in the United States which do an annual business of over one million dollars per year, and the aggregate net sales of this group is about 4 billion dollars per year. An average store in this group would do about 13 million dollars of business per year. Using the percentage expense figures given in the Harvard Business School reports,[1] the payroll expense alone for accounts receivable, accounting office and credit, and marking, is in excess of two per cent of sales or $260,000 per year for

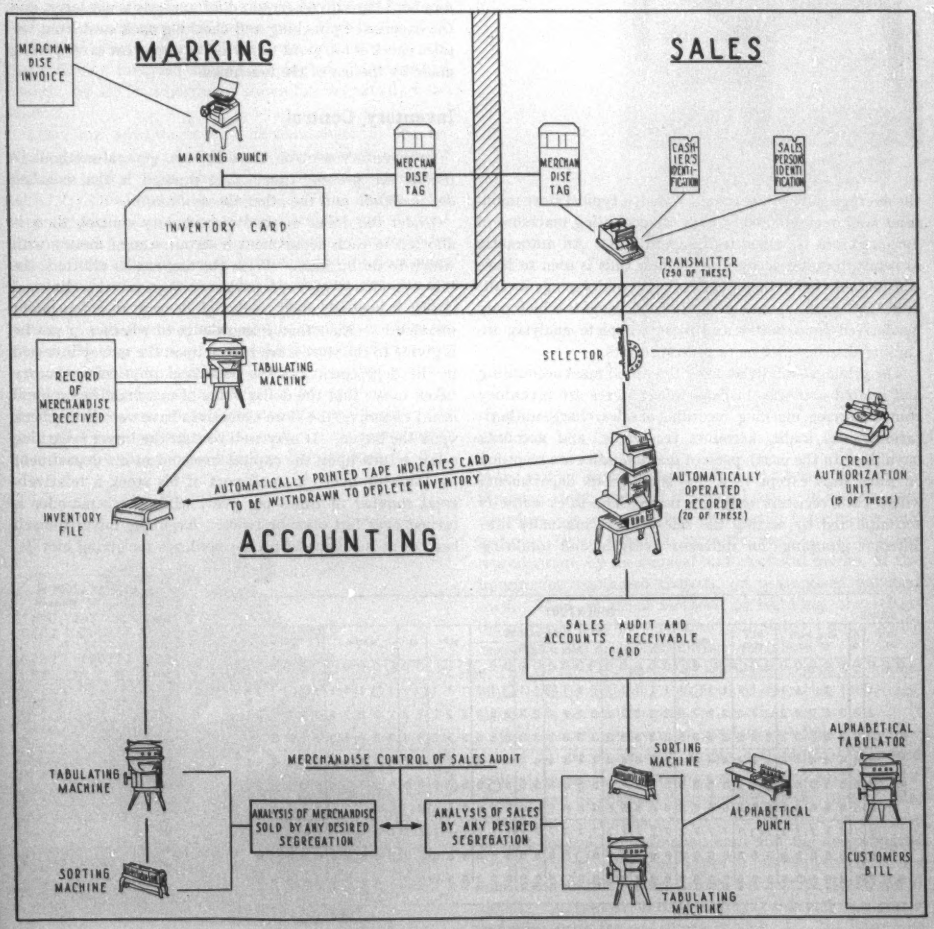


Figure 2. Chart of operating procedure

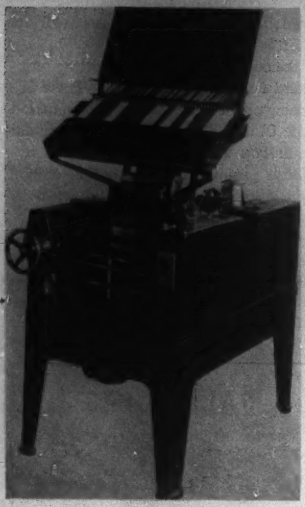


Figure 3. Duplex marking punch

the average store of the group. Such a typical store maintains well over $100,000 worth of accounting machines of various kinds to expedite its operations. An automatic or semiautomatic accounting system thus is seen to have considerable possibility of effecting actual savings in out-of-pocket expense, entirely aside from benefits which may be derived from better and more complete analysis, including speedier and more precise results.

The principal subdivisions of the detail mass accounting and related activities in department stores are inventory control, buying, marking, recording of sales, charge authorization, sales audit, accounts receivable, and accounts payable. In the usual present method, sales are recorded on sales slips except in a few small-goods departments where cash registers only are used. The sales audit is accomplished by sorting the sales checks manually into different groupings for different analyses and totalizing under each grouping. Lost checks are a continual source of worry. Poor handwriting and errors of recording by low-wage employees are handicaps. For each analysis there must be a separate sort, making the manual method slow and costly; and because of this a comprehensive analysis of sales is not economically feasible. A number of stores have already used punched-card machines in the sales audit, but approximately half of these stores have discontinued the punched-card method and gone back to their old plan. A considerable number of stores still continue to use punched cards in sales audit, but it is apparent from the history of the whole group that the benefits are not conclusive evidence of the superiority of that method. The obstacles to the use of punched cards in this work are that the average unit sale is small (about two dollars),[1] the number of groupings required for analysis is not large, and the expense of punching and checking each card from the sales check is too great to permit of any great saving being made by the use of the machines.

Inventory Control

In inventory control, there are two general methods in use at the present time. One method is the so-called *dollar control*, and the other the *unit control*.

Under the dollar method of inventory control, there is allotted to each department a certain sum of money with which to do business. With the amount so allotted, the buyer in charge of the department buys merchandise and conducts business much as though he were an independent merchant. Other than a knowledge of whether or not he is giving to the store a fair return upon the money invested in the department, and a periodical physical inventory taken to see that the dollar value of merchandise on hand is not excessive, the store executives have very little check upon the buyer. It may well be that the buyer is earning a fair return upon the capital invested in his department by "turning over" a small part of his stock a relatively great number of times per year, while the remainder is turned over but once or twice. Even the buyer himself has not at his disposal proper facilities for giving him de-

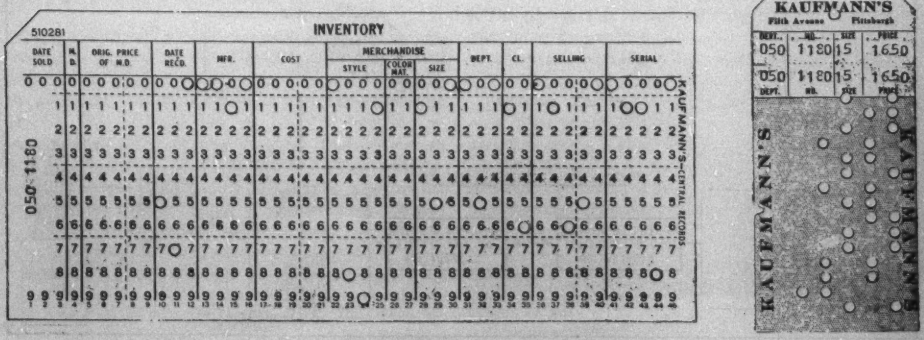


Figure 4. Unit inventory card and corresponding price tag

tailed knowledge of the merchandise in his department, and its turn-over.

Under the unit method of inventory control, a record is kept of each individual article of merchandise as it comes into the store. When each article of merchandise is sold, immediate note of the sale is made on the inventory records so that there is kept a running up-to-date record of the inventory on hand. Under this method, the executives and department heads may know at all times not only the dollar value of merchandise on hand but also just what the description is of this merchandise. They are able to determine what merchandise is moving and what is not, also what merchandise is being handled at a profit and what is not. Under this method, it is possible to keep the inventory at the lowest point consistent with having a sufficient amount and variety of merchandise on hand to meet the requirements of customers. This is the ideal method of inventory control, but because of the cost and the difficulty involved in the keeping of the necessary records, its use in department stores has necessarily been limited.

There are advantages and disadvantages in the recording of sales by cash register only as against the use of the sales book. Using the register, there is more opportunity for theft, and in the aggregate this is known to be very appreciable. Cash-register receipts for various amounts are soon scattered all over the floor in many sales areas. They offer no means of identifying the particular merchandise sold. On the other hand, cash registers are quick and do not waste time of either customer or sales person. Sales slips are more widely used in department stores. If they are used in connection with carrier systems, usually tubes, there is a time-consuming wait for change and receipt, aggravating to the customer. During busy seasons some departments are temporarily changed over from sales-slip to cash-register recording so as to increase the speed of handling transactions.

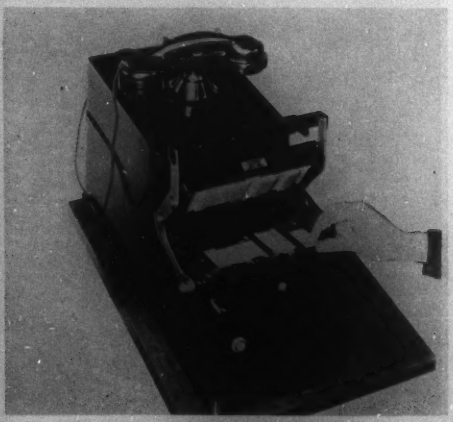
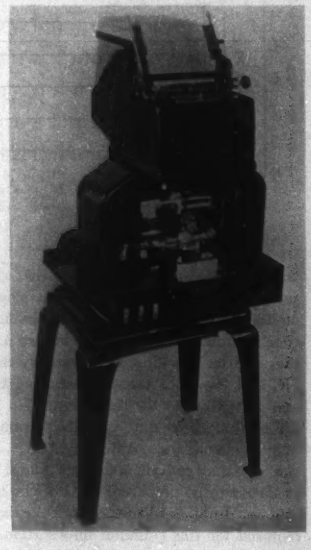


Figure 5. Central records transmitter

Outline of Operations of Remote-Control Accounting System

The factors involved in a sale are: (1) the customer, (2) the merchandise and its selling price, (3) the sales person, and (4) the cashier. In the system to be described, each of these factors is identified by a small punched tag, illustrated in figure 1. In a charge transaction, identification of the cashier is unnecessary. In a cash transaction, identification of the customer is unnecessary. In any one sale therefore it is necessary to identify only three of the four factors. These punched tags are used to control the reproduction, by mechanical and electrical means, of the information contained thereon, on a standard punched card. Then by usual methods of handling, the reproduced cards may be sorted and tabulated automatically to perform the major accounting operations.

Figure 6. Central records recorder



The detailed operation of the system may be understood best by following the chart of operating procedure, figure 2, in connection with the description.

In the marking room, a specially-developed machine (figure 3) simultaneously prints and punches standard tabulating cards for inventory record, and price tags for display and mechanical reproduction at the time of sale. For goods whose value and character warrant the expense of unit control, an individual card and tag are prepared for each piece. For other types of merchandise there are variations in the system, which will not be described in detail. A typical unit inventory card and the corresponding price tag are shown in figure 4. The inventory cards are tabulated and listed, and totals checked against

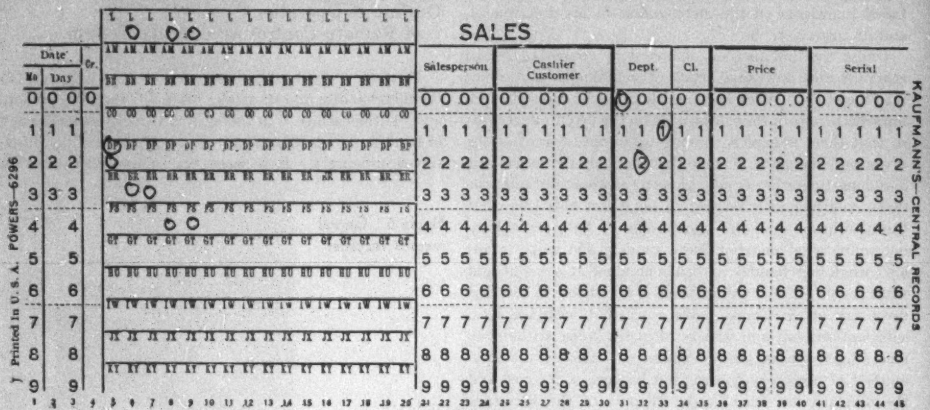


Figure 7. Sales record card

the invoices. It is to be noted that these cards and the price tags are both prepared by a single keyboard setup on the duplex punch illustrated in figure 3, and that a check of the inventory cards is also a check of the price tags. After checking, the inventory cards go to the stock file, and the price tags are attached to the merchandise and go with it to the sales area. An important point in the marking procedure is that the punching is done on a quantity basis, and not item by item. A shipment of merchandise may contain 500 items, and if 500 unit inventory cards are to be prepared, most of the information will be common to all, and but a single keyboard setup will be required for this common information. If this information is checked for one card, it is checked for all. There will be of course some information which is not common to all, but the keyboard changes made in one field of the card do not disturb those in other fields. When producing duplicate cards and tags, the marking punch shown in figure 3 has an output of 100 per minute.

Let us follow the tagged merchandise to the sales area. When a piece of merchandise is sold for cash, the merchandise tag is torn from its stub, which contains duplicate printing of the merchandise identification for use in case the merchandise is returned for credit later by the customer. The detached portion of the tag, along with a punched celluloid token bearing in code the identificaton number of the sales person, and a similar token for the cashier, are placed in a *transmitter*, illustrated in figure 5. When the top of the transmitter is closed (provided it contains all three of the tokens), through appropriate wiring and automatic selector switches it is immediately connected to an idle *recorder* (figure 6) in a central accounting office. All the information needed for a complete record of the sale is automatically transmitted from the punched tokens and reproduced on a standard punched card, and is also printed and totaled on the recording machine.

Transmitting the record of the sale takes five seconds, and at its completion the merchandise tag is automatically stamped with the date of sale, and the top of the transmitter opens. The stamped tag is given to the customer as a receipt, and it identifies the exact merchandise and the price at which it has been sold.

The sales record card produced at the central office is reproduced in figure 7. All the information punched on the right-hand half of the card is obtained from the transmitter. The date only, which occupies the extreme left-hand field on the card, is set up each morning on the recorder punches, and reproduces on all cards punched that day. The large alphabetical field in the left central part of the card is not used on cards which record cash transactions.

The sales audit is obtained from the sales cards by sort-

Figure 8. Charge authorizing unit

ing and tabulating them by machine in the usual way. This part of the work includes reports of cash by cashier, sales by sales person, sales by department, and for the entire store.

The merchandise piece number or serial number on the sales record card serves as a means of identifying, in the

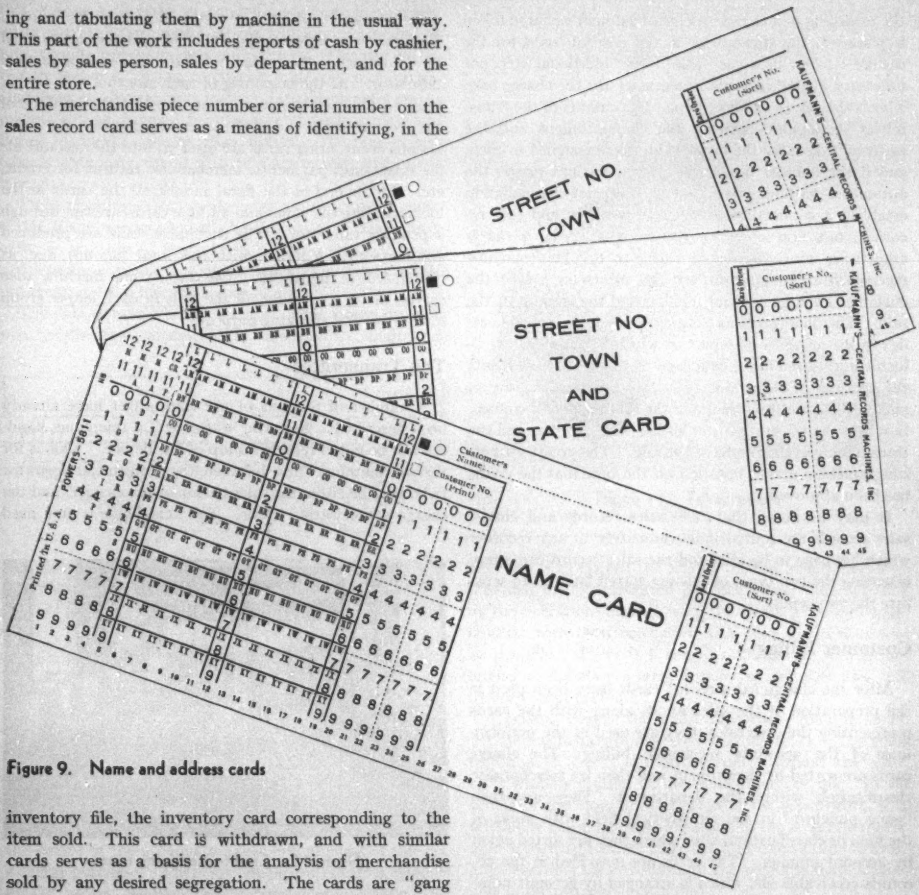


Figure 9. Name and address cards

inventory file, the inventory card corresponding to the item sold. This card is withdrawn, and with similar cards serves as a basis for the analysis of merchandise sold by any desired segregation. The cards are "gang punched" with the date of sale. Among the reports which have been found most useful from these cards are analyses of fastest selling items and styles, turnover by manufacturer, turnover by department, number of items by size, gross profit by manufacturer and by department, and sales by price lines. All these analyses and many more are obtained without any further detail work, but merely by the operation of sorters and tabulators whose speeds are respectively 400 cards per minute and 150 cards per minute. There is a possibility of human error coming in during the operation of withdrawing the inventory cards from the file, but this has been practically eliminated by *totaling the serial numbers* of the sales record cards, which is done automatically, and if the totals check the probability of error is very small indeed.

The cards remaining in the file represent merchandise on hand, and highly useful and valuable information can be drawn from them. Reports which were regularly prepared from this file in a large experimental installation included a weekly summary of merchandise on hand; a monthly analysis by department of the age of merchandise on hand in dollar value and in pieces; an analysis of markdowns for the month by manufacturer, by price line and by reason; a monthly analysis of returns to manufacturer; a quarterly analysis of merchandise in each department classified by size, and size distribution for sales and inventory compared and brought into proper balance.

A file of "on order" cards is also maintained, and used as a basis for analysis of merchandise on order.

Charge Sale

When a sale is made to a customer who has a charge account, there is a somewhat different procedure. All charge customers are supplied with punched celluloid identification tokens, similar to the usual charge tokens except that the account number is punched in code. In

the recording of a charge sale, the customer's charge token is placed in the transmitter in the position used for the cashier's token in a cash sale. One additional step not necessary in the cash sale is necessary for the charge sale. This is the *charge authorization*. The circuits of the transmitter distinguish between the charge tokens and the cashiers' tokens by the range of numbers assigned to each, and if the number lies in the charge account range, the automatic switching equipment does not immediately establish a connection between transmitter and idle recorder, but first connects the transmitter to a *charge authorizing unit*, illustrated in figure 8. This machine receives from the transmitter and prints on a tape the customer's charge account number and the amount of the sale. The charge authorizing clerk refers to a visible-index quick-reference file, part of which is shown in the illustration, to see if the condition of the account warrants the approval of the credit. If so, she operates the button marked OK, and this results in the establishing of connection between the transmitter and an idle recorder, and the transmitting of the record of the sale. The credit authorizing machine makes notation on the tape that the credit has been approved.

It may be noted that cash sales records and charge sales records are routed indiscriminately to any recorder which happens to be idle, and the sales record cards representing the two types of sale are sorted later on to separate the two types.

Customer Billing

After the charge sales record cards have been used in the preparation of the sales audit, along with the cards representing the cash sales, they are used in the performance of the accounts receivable billing. The charge cards are sorted by department and then by merchandise classification within the department. They are then "gang punched" in the alphabetical field with *name* of the item or classification, after which they are sorted again by account number. The cards are now filed in the accounts receivable file, which is arranged by account number. During this work a dollar total by ledger groups is used as a control check.

The accounts receivable file for each account contains a series of name-and-address cards, illustrated in figure 9. These serve as index cards in the file, and also act to head up the bill when the cards are fed through an alphabetical tabulator. At the beginning of each month a new card is inserted for each active account, showing the balance of the account at the end of the preceding month. As transactions occur, other cards are inserted into the account file for sales, cash payments, merchandise returns for credit, etc. At the end of the fiscal month all the cards in the file, including the name-and-address cards, are run through a printing tabulator. The customers' bills are produced automatically, together with the total amount due, as illustrated in figure 10. The tabulating machine also carries along a total for all the bills in each ledger group for control and checking purposes.

MODEL DEPARTMENT STORES

BOSTON

SOLD TO — ACCOUNT NO.

MRS PAUL D CHANDLER — 30036
1289 BEACON STREET
CAMBRIDGE MASS

AMOUNT

Balance Brought Forward — PLEASE ENCLOSE THIS STUB WITH YOUR REMITTANCE. YOUR CANCELLED CHECK SERVES AS YOUR ACKNOWLEDGMENT OF A CREDIT.

MODEL DEPARTMENT STORES		ACCOUNT NO. 30036			
DATE	ITEM	DEPT. CLASS.	CREDITS		CHARGES
806	SCARF	28038			4 50
803	HAT	47819			17 00
803	PAJAMAS	89127			10 00
808	DRESS	95026			25 00
809	PR HOSE	38481			2 95
815	SCARF	28038	4 50		
	NET AMOUNT DUE				50 45

Figure 10. Automatically prepared customer's bill

The Transmitter

A number of features of the transmitter have already been described. Referring to figure 5, a telephone handset will be noted resting on top of the device. This is for verbal communication between the transmitter operator (who may be either the sales person or the cashier) and the charge-authorization clerk. The telephone is not used unless there is some question relative to the approval of the credit, and if the authorization clerk desires to converse, she operates a button which causes a light, shown at the left front of the transmitter, to glow. The telephone circuit is already connected by automatic switching, and the transmitter operator has only to lift up the telephone and start talking. In designing the system, it was felt that in the delicate business of passing on the credit standing of the customer, the importance of preserving good will required the flexibility of handling afforded at a distance only by telephonic communication.

Figure 11. Credit-authorizing room

Electrical interlocks are provided in the transmitter so that failure to put in one of the tokens, or putting in a token in the wrong position, will prevent the transmitter top from locking down when closed, and also prevent the operation of the selector switches and the sending of the record. Two or more transmitters can be connected to a single cable circuit in a "party-wire" relation, and when

this is done a transmitter coming on a busy line merely waits until the termination of the transmission period of five seconds before it goes into action. This party-line feature makes it feasible to provide numerous receptacles, analogous to electric-light sockets, into which extra transmitters can be plugged to take care of peak loads occasioned by special sales or other causes. The plug-in feature is obviously useful also in maintenance and repair work.

The transmitter circuits are arranged so as to be inoperable if the wrong number of holes exists or apparently exists in any one of the tokens. Thus a scrap of paper accidentally covering one of the holes of a token would not result in an erroneous record.

The date of sale, which the transmitters stamp on each merchandise tag transmitted, is embossed by small steel

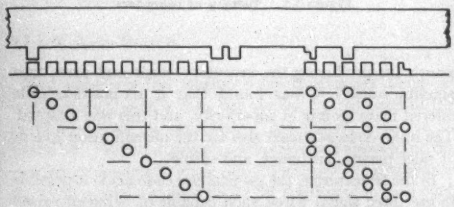


Figure 12. Code bar for punching dual code

stamps, and these have to be changed by hand each day to the new day's date.

Each transmitter contains a circuit which sorts the records and routes the charge sales to the credit authorizing department and the cash sales directly to the recorders.

The Credit Authorizing Machine

The credit authorizing unit, shown in figure 8, receives the record of the account number and amount of sale for a charge purchase. There are five button controls, namely for OK, reject, call back or telephone communication, and two supplementary controls for emergency release and for carriage return. A row of 20 lights in the front of the base is provided to indicate how many calls there are awaiting their turns for being passed upon for authorization. The telephone is at the left of the main unit.

The routing of sales to the credit authorizing machines differs from the indiscriminate method employed for the recorders of selecting any idle machine. Instead, each credit authorizing unit has routed to it by the selector switches only records involving accounts which lie within a specific limited range. The particular unit pictured in figure 8, for example, receives only accounts numbered from 220,000 to 239,999 inclusive, as is indicated by the large numbers just above the row of 20 lights. This routing is accomplished by allowing the first two digits of the customers' charge tokens to control the operation of selector switches which thereupon establish connection to the proper authorizing unit. The purpose of this

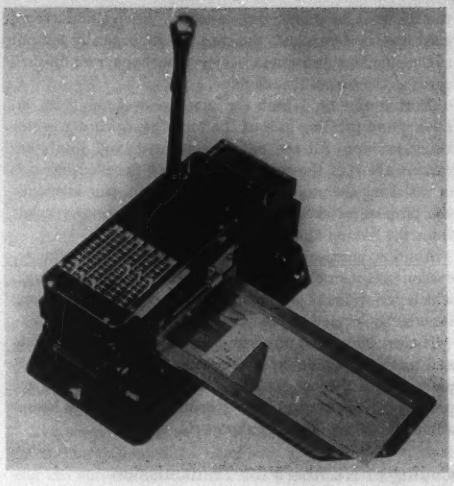


Figure 13. Token punch

selection is to reduce the size of the file which has to be provided for and operated by each clerk, thus speeding up the operations and allowing the clerks to become more familiar with their respective lists than would otherwise be possible. There is a considerable saving also in not having to maintain a large number of complete files, and to keep them posted.

A general view of the credit authorizing room in an experimental installation is shown in figure 11. The room contains 15 credit authorizing units around the sides, each with its section of the quick-reference file. In the center of the room are the desks of the supervisors, with telephone and tube communication to the accounts receivable department where more detailed information is available regarding the conditions of the accounts than is available in the quick-reference files.

The Recorder

The recorder is shown in figure 6. It is a combination of a punch adapted for remote-control operation, and a tabulator. A stack of blank cards is kept in the magazine at the front of the machine, as may be seen in the picture. A card is normally always kept in the punching position, between the punches and dies, and if there should by accident be no card there, then an electrical interlock will prevent the particular recorder from being selected by the automatic switching equipment to receive one of the records. In this event a buzzer is also sounded to notify the attendant. As the message comes in, in normal operation, the punching is not done step by step, but instead a set basket is set up with the entire message, and at the end all the punching is done at one stroke. The date of sale is left set up on the set basket all day, so that

this does not have to be transmitted. When a sales record card has been punched, the card is automatically fed out of the punching position into a receiving hopper for finished cards at the rear of the machine.

During the time that the message is coming in, an adding and printing unit at the top of the recorder is also being set up. All the data are printed, and totals are carried along of the sales prices and of the identification or serial numbers of the merchandise sold, this latter for the purpose of checking withdrawals of inventory cards from the file, as already mentioned.

Another interlock which has been provided on the recorder cuts it out of circuit unless the traveling carriage, which performs the setting up operation on the set basket, is correctly located at the starting position.

If there should be any lost or mutilated cards, the lists and totals are available to check and to make possible replacement of the lost cards. However, since the cards are produced in the central records room, the chance of losing any of them can be made almost nil.

Coding of Numbers for Transmission

The usual coding of digits on punched cards involves merely punching in the proper one of ten positions numbered from 0 to 9 in each column. The use of such a system for transmitting would require a large number of relays and conductors, and would require a wide price tag, which is considered by retailers as a heavy handicap, because it spoils the appearance and attractiveness of the merchandise. It was therefore decided to adopt the expedient of multiple punching for the merchandise tag, using fewer than ten positions in each column.

It is possible to code the ten digits by the use of a minimum of four positions, using four single-hole and six double-hole codes. However, if a double-hole column had one hole accidentally or purposely covered over, there would result an incorrect transmittal, and this could not be tolerated. With five positions it is possible to have ten combinations of just two holes. However, in working out the transmitter circuits and the coding device in the

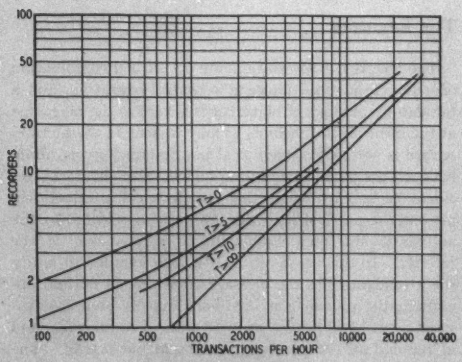


Figure 14. Traffic curves

Figure 15. Battery of recorders

punch for producing the inventory cards and price tags simultaneously, it was found that a six-position code offered many points of superiority, and this was adopted. The same code was used also for the identification tokens of sales person, customer, and cashier.

In the transmitter, the six-position code made it possible to use three signal wires, each capable of being energized positively or negatively, but only two of them to be energized at one time. This offers 12 combinations, of which only 10 are needed. At the central office, a system of relays decoded the message so that the recording machine received the message over 10 signal wires in a single-hole code.

The Marking Punch

The design of the punch for the simultaneous preparation of the inventory card in single-hole code and the price tag in double-hole code seemed to offer some difficulty, and the first machine for the purpose embodied two separate punches with a set of coding relays connected between them. Subsequent thought, however, evolved a much simpler and more effective mechanical method of coding, which is embodied in the present machine shown in figure 3. This machine has a slide keyboard, and as a slide is moved by hand, a steel rod carrying a lug is moved over the tops of the punches below, in the corresponding column. For the part of the punch which serves to prepare the inventory card there is but a single lug, as shown in the left-hand portion of figure 12. A continuation of the same rod carries four lugs, of which one is partly cut away. The top of one of the punches is also partly cut away to match, and as may be seen by studying the right-hand half of figure 12, the same movement of the same slide and rod will produce a two-hole code in the six-position tag while producing at the same time the usual single-hole code in the inventory card.

The actual punching is accomplished by the lifting of the die-plate after the entire setup has been completed. Printing units are provided for both inventory card and

tag, and the setup is accomplished by but a single operation of the keyboard. The inventory card is imprinted only with characters which are needed in identifying it in the file, and the printing is done at one end so that space-saving vertical filing can be used. This is advantageous also in that the fingering does not wear or soften the long edges which are the ones used in the mechanical feeding of the cards.

In the punch, blank inventory cards are placed in a hopper at the front, and blank price tags at the rear. The finished cards and tags are discharged into hoppers at the middle of the machine. There is an indicator to show when one or the other of the magazines runs empty; a counter for the number of cards and tags; the operation may be controlled for a single card and tag or the machine may be made to turn them out continuously at the rate of 100 per minute.

The Token Punch

For punching the tokens, a small lever-set hand-operated punch, with a code bar similar to that used in the marking punch, is provided. This punch is shown in figure 13. When a token is prepared, a duplicate of the punchings is always made simultaneously on a standard tabulating card and filed away for reference, so that even if an error is made in the punching, it can be discovered and rectified later on.

Traffic Density on Central Records System

The number of transmitters required in the remote-control central records system described depends upon the area and arrangement of the selling space of the store, and the criteria are the convenience and saving of time of the sales employees and the customers, as compared to incremental cost.

The number of recorders required depends only on the peak rate of transactions and the time required for recording each transaction. The time required for each transaction is five seconds.

If each recorder were kept busy continuously, it could handle 12 transactions per minute or 720 transactions per hour. However, it is known that the transactions will not occur evenly throughout the hour, but will occur more or less at random. Sufficient additional transmitters have to be provided to take care of the brief peaks of traffic which will take place owing to this random distribution. It is impossible to avoid some possibility of delay in recording a transaction without providing a recorder for each transmitter, which is economically unfeasible. Some practical compromise must be reached between the two extremes mentioned.

The consideration of traffic density is a problem in the theory of probability similar to trunking and other traffic problems in the telephone industry. A solution applicable to the case at hand has been worked out and charted by E. C. Molina,[2] and a set of curves derived from his article is presented in figure 14. The upper curve of the chart, marked "$T > 0$," shows the relation which exists between the number of transactions per hour and the number of recorders required if the system is to be operated on a basis of one transaction out of every hundred on the average being delayed at all in transmitting. For example, if the rate is 10,000 transactions per hour, then 24 recorders would be required on this basis.

The second curve of the chart, marked "$T > 5$," indicates the relation of the number of transactions per hour and the number of recorders where one transaction out of each 100 would be delayed more than five seconds before transmitting. On this basis there would be required only 17 recorders to take care of 10,000 transactions per hour.

The third curve, marked "$T > 10$," represents the relation existing when one transaction out of 100 will meet with a delay of more than ten seconds before being transmitted.

Naturally, the number of recorders which can be depended on for continuous use will be one or two less than the total number installed, to allow for repairs and maintenance.

The numbers of the different units in the experimental installation were: 250 transmitters, 20 recorders, and 15 credit authorizing units, to handle a peak transaction rate of 9,000 per hour, of which about half were charge transactions. During very busy times, however, charge transactions of very small amount are allowed without specific reference to the credit authorization files.

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Line-to-Line Faults on A-C Network Feeders

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Synopsis

This paper deals with the magnitude of currents in a secondary a-c network due to a line-to-line fault on the high-voltage feeder, and gives the analysis of the double-unbalance circuit resulting when a network protector fails to open during such a fault, and one of the protector fuses blows. Results of field tests made on an actual network are included.

Introduction

IN a low-voltage network, the network protector is designed to open automatically for all faults on the high-voltage feeder supplying the network. In order to provide back-up protection in case a protector fails to open for a feeder fault, fuses are incorporated in the phase leads of the protector. The minimum rating of these fuses is limited to some extent because the fuses should not blow for faults on the low-voltage network. On the Commonwealth Edison Company a-c network, the fuses used on 300-kva transformer banks are rated at 1,500 amperes and those on 500-kva banks at 3,000 amperes.

With the rating of fuses limited by the restriction given above, it is desirable to determine whether or not the various types of primary faults will cause the fuses to blow, in case a protector fails to open for some reason or other. Calculations show that for three-phase faults the magnitude of the fault currents in a typical network, will always be great enough to blow the protector fuses. For line-to-ground faults on the primary feeder, the magnitude of the current through the fuses is well below the fuse rating, because the transformer bank is connected wye-delta. Hence, fuses cannot clear the transformer bank for line-to-ground faults. For line-to-line or two-line-to-ground faults, the analysis of the circuit is more complicated. These types of faults cause unequal currents to flow through the fuses and in many cases only one of the three fuses will blow. The purpose of this paper is to show the results of an investigation made to determine the magnitude of currents in a network for line-to-line faults. This investigation included field tests as well as an analytical study.

Figure 1 is a one-line diagram of a typical network system. The secondary of this system is four-wire, using single-conductor lead-covered cable, the neutral consisting of a copper conductor in parallel with its sheath and the sheaths of the phase cables. Figure 2 shows the flow of currents in the network due to a line-to-line fault on the primary feeder, after the feeder breaker at the station has opened. It will be noted that one fuse carries twice the value of current flowing in the other two fuses. It can be shown that the value of current in the fuse carrying the greatest current is equal in magnitude to the current which would be carried by the fuse for the case of a three-phase fault. In all cases this value of current is great enough to cause the fuse to blow. At the time this fuse blows the remaining two fuses will be intact since they carry only half the value of current. Figure 3 shows the circuit conditions resulting after the first fuse has blown. The current now flows through the two remaining conductors and returns over the neutral path. Since the impedance of the neutral path is comparatively high, the value of current flowing through the two fuses decreases in value after the first fuse blows. This reduced value of current in many cases will not be high enough to blow the two remaining fuses and the transformer bank will not be cleared from the network. If there is more than one transformer bank in a single vault, the reduction in current after the first fuse blows, will not be great enough to prevent the remaining fuses blowing.

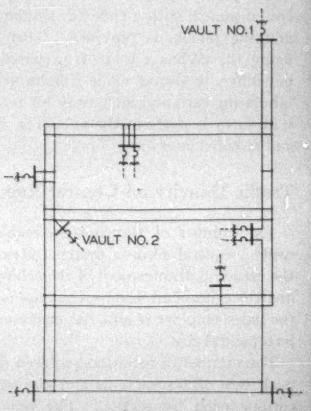

Figure 1. Typical low-voltage a-c network

Discussion of Calculations

The solution of the circuit for the conditions shown in figure 2 presents no unusual problem. The fault currents flowing in the circuit of figure 3 were first determined by

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E. L. MICHELSON and NOBLE G. LARSON are both engineers for the Commonwealth Edison Company, Chicago, Ill. The authors wish to thank Professor Edward W. Kimbark, Polytechnic Institute of Brooklyn, for the development of the general equations for the solution of this problem by the method of symmetrical components.

For all numbered references, see list at end of paper.

solving the simultaneous circuit equations based on Kirchhoff's laws. However, it was recognized that this circuit was an interesting case of problems dealing with simultaneous faults on a balanced three-phase system, and could be solved using the method of symmetrical components. The two simultaneous faults in this case are the line-to-line fault on the high-voltage feeder and the open-circuit in the phase in which the low tension fuse is blown. The analysis of the problem using the method of symmetrical components is shown in the appendix. The results obtained using this method checked of course with those obtained using the first method, and the labor required for the solution was considerably shortened.

Table I gives the results of calculations made to determine the value of current flowing through the transformer windings for the case of a line-to-line fault on the high-voltage feeder, after the feeder breaker has opened. The equivalent system behind this transformer which was not cleared has been expressed in terms of an equivalent length of secondary cable between this transformer and the remainder of the system.

Description of Tests

In order to check the accuracy of the assumptions made in these calculations, it was decided to perform tests on a section of the actual a-c secondary network of the Commonwealth Edison Company, shown in figure 1. Tests were made at locations designated as vaults number 1 and number 2, which are supplied from the same high-voltage feeder. The fault was applied by closing two line disconnects to ground at the station, and was initiated and cleared by means of the station oil circuit breaker. At each location two tests were made: first with the *A* phase fuse removed and second with all fuses in. Table II gives the results of these tests.

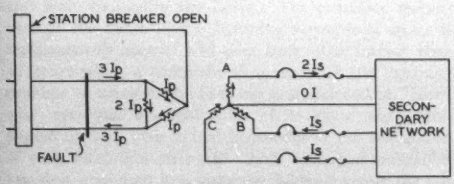

Figure 2. Flow of current in a network due to a line-to-line fault on the primary feeder

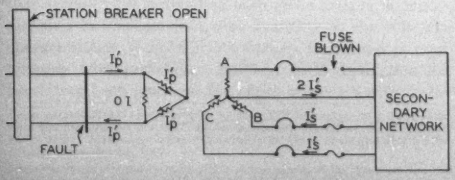

Figure 3. Flow of currents in a network, due to a line-to-line fault on the primary feeder, with the A-phase fuse blown

Discussion of Test Results

At both test locations, when the fault was applied with the *A*-phase fuse in, only this fuse was blown. The current was reduced to such a value in the remaining phases that these fuses did not blow and the fault was cleared by opening the oil circuit breakers at the station.

The test values checked essentially with the calculated values of current. The results verified the assumption that the effect of the stray ground current was unimportant. It will be noted that the current in the *B* and *C* phases is reduced to approximately 50 per cent of the initial value in both calculated and test results.

Table I. Transformer Secondary Currents for Line-to-Line Feeder Faults

Transformer Kva	Fuse Size (Amp.)	Equivalent Length of Secondary Mains to Banks Supplying Fault Current	Approximate Fault Current Before first fuse blows A	B	C	After first fuse blows B	C
300	1,500	100 feet	9,900–4,950–4,950			3,150–3,150	
300	1,500	200 feet	7,000–3,500–3,500			1,860–1,860	
300	1,500	300 feet	5,600–2,800–2,800			1,320–1,360	
300	1,500	400 feet	4,500–2,250–2,250			1,020–1,020	
500	3,000	100 feet	13,100–6,550–6,550			3,600–3,600	
500	3,000	200 feet	8,600–4,300–4,300			2,000–2,000	
500	3,000	300 feet	6,300–3,150–3,150			1,400–1,400	
500	3,000	400 feet	5,000–2,500–2,500			1,060–1,060	

NOTE: Calculations based on 5 per cent impedance transformers, four single-conductor cables in a duct, 350,000-circular-mil phase cables, and 4/0 neutral cable, the arrangement of conductors assumed to be a square with the conductors as close together as possible. The effect of stray ground current was neglected.

Table II. Results of Tests

	A-Phase Fuse Out	*A*-Phase Fuse In
Vault 1		
A-phase amperes	0	5,680
B-phase amperes	1,500	2,840
C-phase amperes	1,500	2,840
Vault 2		
A-phase amperes	0	10,400
B-phase amperes	2,700	5,200
C-phase amperes	2,700	5,200

Appendix—Solution of Circuit of Figure 3, by Method of Symmetrical Components

The circuit of figure 3 can be solved on an a-c calculating board by setting up the sequence networks as shown in figure 4.[1] The open circuit in phase *A* is represented by connecting the three networks in parallel at points *y* and *z* as shown by the dashed lines. The line-to-line fault on phases *B* and *C* is represented by the connection between the positive and negative sequence networks. This connection must be made through one-to-one insulating transformers and because of the delta-wye transformation, the polarity of the

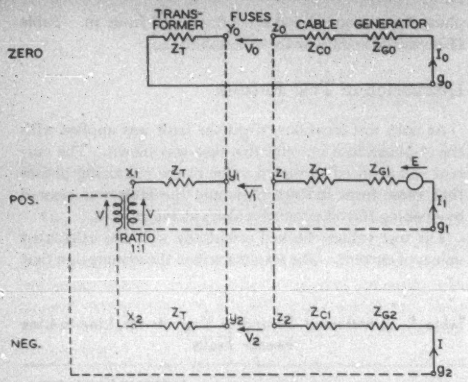

Figure 4. Calculating board set-up for the solution of figure 3 by the method of symmetrical components

insulating transformer must be reversed from the normal method of connection.

The algebraic solution of this circuit is as follows:

Relation between currents:

At open circuit: $I_0 + I_1 + I_2 = 0$ (1)

At short circuit: $I_2 = I_1$ (2)

Equating voltages between points y and z

$v_0 = v_1 = v_2$ (3)

or

$I_0 Z_0 = -E + I_1 Z_1 + V = I_2 Z_2 - V$ (4)

where

V = voltage across the one-to-one transformer.

Z_0, Z_1, Z_2 are the sum of the impedances in the respective networks.

Eliminating I_0, I_2, and V from (4), we find

$E = I_1(Z_1 + Z_2 + 4Z_0)$ (5)

Let i be the actual value of current flowing through the transformer winding. (I_a' of figure 3.)

$$\begin{aligned} I_1 &= 1/3(I_a + aI_b + a^2 I_c) \\ &= 1/3[0 + a(-i) + a^2(-i)] \\ &= 1/3i \end{aligned} \quad (6)$$

Therefore

$$\begin{aligned} E &= i/3(Z_1 + Z_1 + 4Z_0) \\ &= i/3(Z_{T1} + Z_{C1} + 4Z_{T0} + 2Z_{C1} + 4Z_{C0} + 6Z_T) \end{aligned}$$

Where

E = Phase-to-neutral voltage on low-voltage network

and

I_1, I_2, I_0 are the sequence currents in the respective networks.
i = actual current in transformer winding. (See figure 3.)

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Lightning Strength of Wood in Power Transmission Structures

By PHILIP SPORN
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J. T. LUSIGNAN, JR.
MEMBER AIEE

I. Introduction

ALTHOUGH wood has been known to possess the excellent properties of mechanical strength in combination with insulation strength almost since the beginning of the electrical art, its real lightning strength was not generally appreciated until within comparatively recent years. It is true that it was rather extensively used in the past to supply power frequency insulation in treated form alone or with transil oil. For example, wood either solid or laminated has been employed for years in operating rods on oil circuit breakers and in terminal and spacing blocks in transformers. The 60-cycle strength of wood under those conditions has been studied, and although the results were not made available generally, the strength factors had been known with considerable preciseness for some time. In these applications, however, the 60-cycle (i.e., power frequency) strength of wood has been of paramount interest, and the lightning or impulse insulation value of secondary interest, either because the latter was considered comparatively unimportant or because the impulse strength furnished by other insulating members or mediums in the structure was considered sufficient.

The use of wood as supporting structures in transmission and distribution circuits goes back to the beginning of the power distribution art. Here, although it has not been generally realized, the lightning or impulse value of the wood has been utilized consciously or unconsciously and more frequently the latter. The conscious realization of the value of the lightning strength of wood is comparatively recent[1] and goes back little further than 12 years when a comprehensive study of the lightning problem on transmission lines was first undertaken. However, even this late realization of its value was accompanied by very little actual knowledge of the mechanism of such insulation strength. Such conscious realization was first presented in a paper by Melvin[2] giving the impulse insulation characteristics of wood and of wood in combination with insulators. A number of other investigations [3–8] have been described since then, each of which added to our store of knowledge. However, it was felt that certain vital factors had been given little or no study, and that insufficient data were available on the volt-time characteristics of wood in its various forms and in combination with porcelain. Further, little distinction has heretofore been made on the effect of the polarity of the impulse on wood flashover. Again, few test data have been given on actual assemblies of full-fledged transmission lines.

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1. For all numbered references, see list at end of paper.

II. Purpose and Scope of Investigation

In the light of the above, the authors undertook a very comprehensive investigation of the lightning strength of wood alone, as used in transmission structures, and in combination with porcelain insulators (pin and suspension) to determine:

(*a*). The volt-time characteristics of the materials in question.

(*b*). Polarity effects, that is, the variation of the characteristics with positive and negative surges.

(*c*). The effect of moisture.

(*d*). The effect of age.

(*e*). The effect of the material employed, such as cedar, pine, and fir.

(*f*). The effect of treatment, particularly creosoting which is coming more and more into common use.

In the course of this investigation actual impulse tests were made on pole structures as used in the past few years on transmission lines, both for 33-kv and 66-kv service. Here tests were carried out on actual pole-line assemblies as they existed before and after structural changes were made to take advantage of the wood impulse insulation strength.

III. Test Equipment and Procedure

All of the flashover studies were carried out in the Ohio Brass High-Voltage Laboratory at Barberton with surges applied from the 3,000,000-volt impulse generator. The standard $1^1/_2$ by 40-microsecond wave was used, thereby allowing comparison with the impulse data of other insulation for the purpose of system co-ordination. Both positive and negative surges were applied in practically all cases, and oscillograph records were secured of the resultant voltage waves. From these oscillograms the volt and time data were taken for plotting the various curves here given.

Figure 1 illustrates some of the typical oscillograms, with impulses applied ranging from full waves to waves resulting in flashover of the structure under test in 1.8 microseconds. The nesting of the curves, as shown, is a very effective method of accurately correlating the records as the test work progresses, as well as greatly reducing the time otherwise required in changing film.

All flashover values were corrected to standard air density conditions. Inasmuch as no humidity correction factor for wood has been established as yet, no corrections were made for this atmospheric factor. To make possible

a proper comparison therefore of wood, porcelain, and air-flashover values, the latter two were corrected to the humidity at which the wood specimens were tested.

The wood crossarms studied consisted of typical specimens of untreated and creosote dipped Douglas fir, and creosote impregnated pine. Crossarm sizes varied from three and one-half by four and one-half inch to six by eight-inch cross section. In most cases new and old specimens were used, the latter having seen varying years of field service up to about ten years. For pole members, red cedar and creosoted pine were used, new and similar old specimens being chosen here as well.

Various lengths of individual wood specimens were flashed over in order to determine the impulse strength furnished by each. Braided copper bands which could be moved along the wood were employed as electrodes, and the wood lengths tested varied from a few inches up to eight feet. Voltage from the impulse generator was always applied to one band while the other band was grounded. In each case the wood specimen was suspended at a distance from ground equal to several times the length of gap being tested, in order to allow as little interference as possible with the field surrounding the wood gap. In securing flashover data upon successive lengths of the same specimen, care was taken to avoid wood surfaces which were too badly splintered from previous discharges. A certain amount of splintering had no appreciable effect upon the flashover voltages, although badly shattered members showed some reduction of insulation strength.

Tests were made on combinations of wood and porcelain to determine the total insulation strength afforded. In these studies varying sizes of pin-type insulators and lengths of suspension strings were used. These were mounted on the several types of crossarms noted above and flashover made with different lengths of wood in series with the insulator units. In this way the effect of various combinations of porcelain and wood insulation were investigated. An effort was made to confine the tests to combinations which were typical of field installations. Figure 2 illustrates such a typical specimen on test.

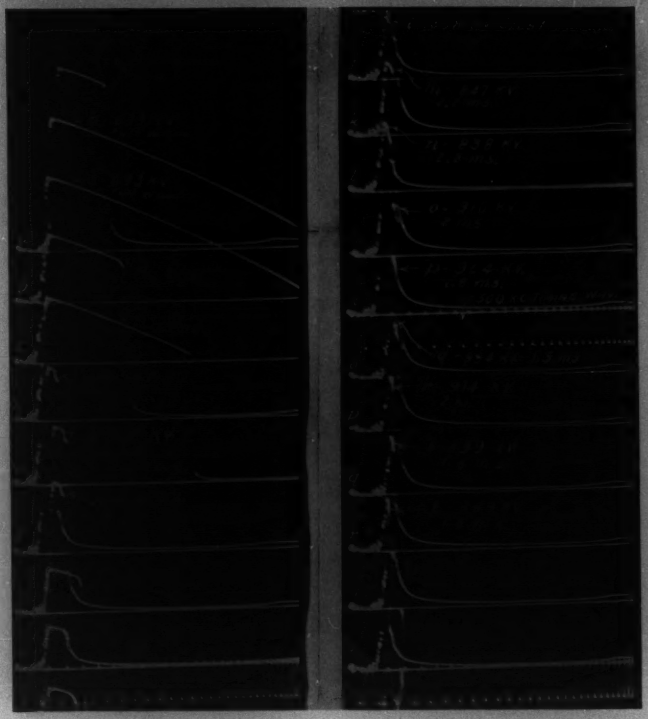


Figure 1. Typical oscillograms of impulse tests on wood and wood-porcelain structures. The above tests were made on three 5- by 10-inch suspension insulators plus four feet of creosoted pine crossarms with 1½x40 microsecond positive polarity

IV. Test Results—Structure Members

1. Crossarms

Eleven crossarm specimens of the three types of wood previously noted were given impulse flashover tests, and volt-time curves plotted from the oscillograph data. Figure 3 illustrates two sets of such curves for 12-inch and 36-inch wood gaps. Corresponding NEMA rod-gap curves are also given in order to show the comparative volt-time characteristics of air gaps. In figure 4 are given the minimum and two-microsecond flashover values for various lengths of wood arms.

These arms were of various cross sections. It being quite apparent from the test data that cross section is a vital factor in the impulse flashover value of an arm an effort was made to determine the effect of this factor upon impulse insulation strength. Accordingly, new curves were plotted of flashover voltage against cross-sectional area. Figure 5 (*A* and *B*) shows such curves for creosoted and untreated fir, and creosoted pine. It will be noted that these are practically straight lines with flashover

Figure 2. Typical impulse flashover in the laboratory of 33-kv pin insulator plus two feet of creosoted Douglas fir crossarm

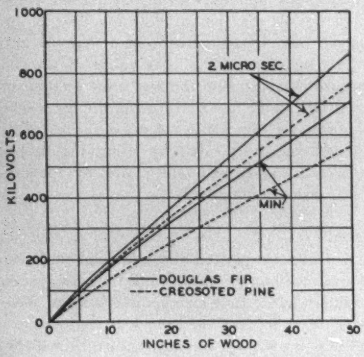


Figure 4 (left). Impulse flashover of Douglas fir and creosoted pine crossarms. Average of positive and negative average values. Two-microsecond and minimum values only are given

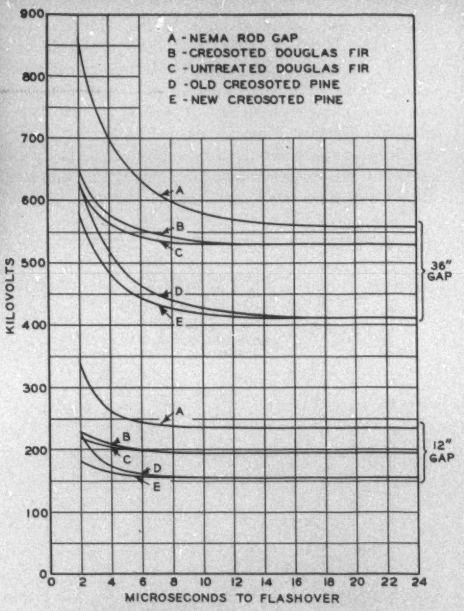
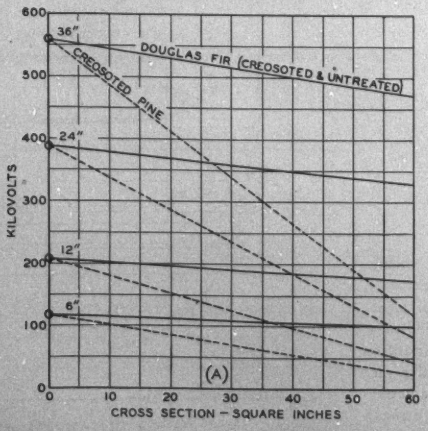
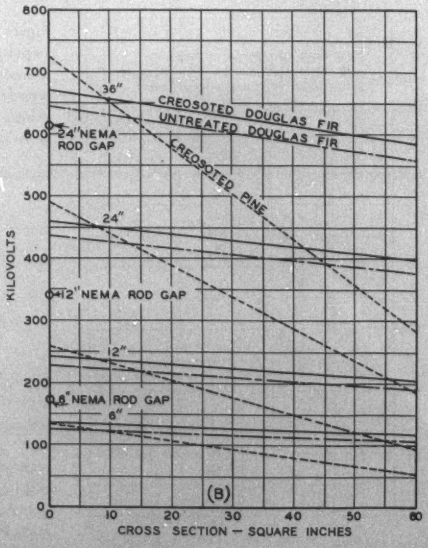


Figure 3. Impulse flashover of wood crossarms of 20-square-inch cross section; positive polarity

Figure 5. Effect of wood cross section on impulse flashover of fir and creosoted pine crossarms

A—Positive polarity; minimum flashover
B—Positive polarity; 2 microsecond flashover





decreasing with increased cross section. Most of these data were obtained at a humidity of 0.4 inch of mercury-vapor pressure. The NEMA rod-gap flashover values for this humidity were selected and plotted for zero cross section of wood. It will be noted that at minimum flashover these air-gap values lie on the wood flashover curves. For the 2-microsecond points they lie above the wood curves, indicating that the air gap has a steeper volt-time curve, and therefore greater time lag than the corresponding wood gap. This decrease of flashover strength with increase of cross section is probably due to the fact that there is a greater chance of weaker flashover paths, the larger the wood cross section. Obviously, too, the larger members have more chance of retaining internal moisture and other impurities which lessen the insulation strength. It will be noted, too, that the steepness of the curves is greatly influenced by the class of wood and treatment. The rapid decrease of strength in the case of the pine arms was unexpected and further work is to be done to check this.

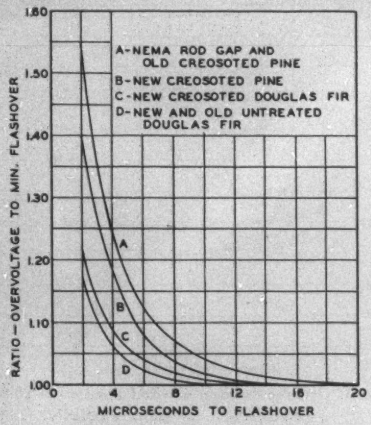


Figure 6. Volt-time characteristics of 36-inch crossarms, 20-square-inch cross section, of various woods, positive polarity

In figure 6 there is plotted a form of volt-time curve expressing ratios of overvoltage to minimum flashover in order to permit a direct comparison of the insulating properties of the various materials involved. It will be noted that the rod-gap curve is the highest one of the group. Its characteristics are approached only by the creosoted pine members, the old pine having been found to lie approximately on the air-gap curve. These curves also illustrate why the minimum flashover values of the rod gap on figure 5*A* coincide with the zero cross sections of wood, whereas the 2-microsecond values do not. The corresponding true volt-time curves of any of the materials shown obviously can be plotted by using the proper minimum flashover values and multiplying by the corresponding ratios shown in figure 6.

2. Wood Poles

In figure 7 there are plotted the minimum flashover voltage values of various lengths of pine and cedar poles. In order to illustrate the time-lag characteristics of these members, volt-time curves of the eight-foot sections have been plotted in figure 8. On this figure are included cor-

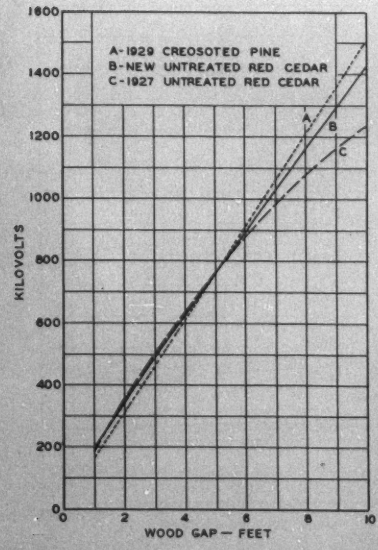


Figure 7 (left). Impulse flashover characteristics of wood poles, minimum positive polarity

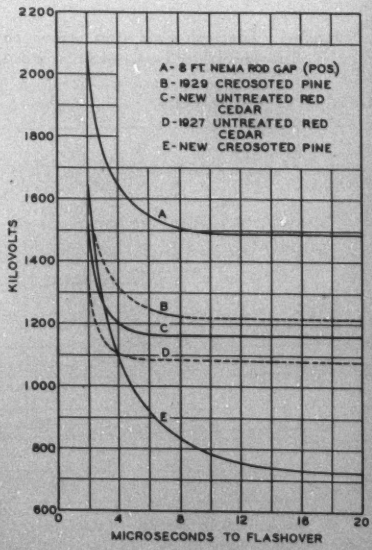


Figure 8 (right). Volt-time characteristics of eight-foot wood-pole sections (positive and negative values are approximately equal)

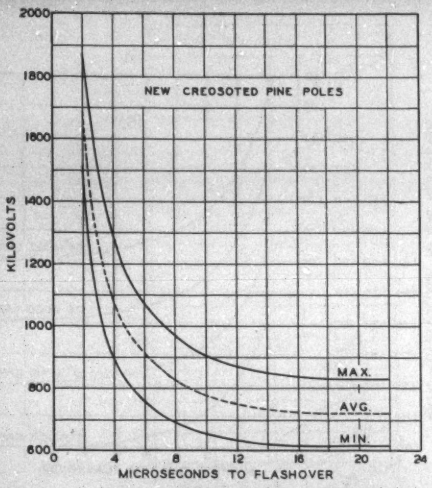


Figure 9. Variation in impulse flashover characteristics of wood poles; eight-foot length; positive wave (positive and negative values approximately equal)

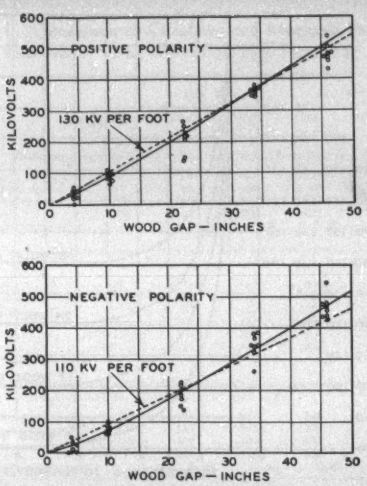
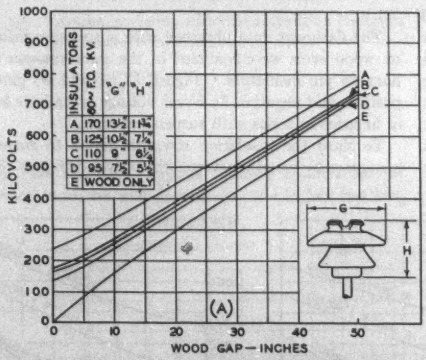
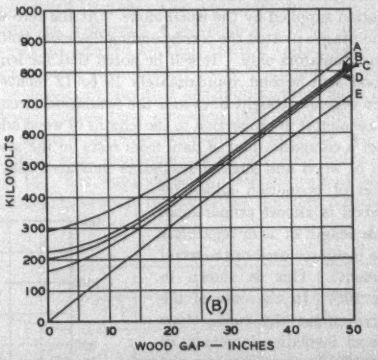


Figure 10C. Impulse insulation added to pin insulator by creosoted or untreated fir crossarm; minimum wave values. Insulators used same as shown in table of figure 10A





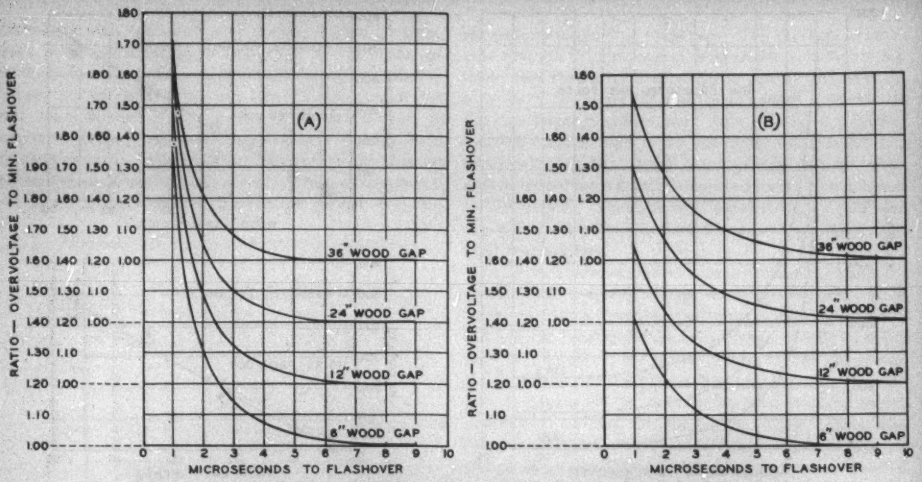
Figures 10A and 10B. Impulse flashover characteristics of pin insulators plus creosoted fir crossarm; minimum flashover

A—Positive polarity *B*—Negative polarity

responding spacings of rod gap and newly creosoted pine poles. It will be noted that the latter two represent the upper and lower limits respectively of insulation strength. A further examination will show that at minimum wave values, the insulation value of the plain rod gap is as much higher than the older wood members as the latter are higher than the newly creosoted pine poles. The last were tested within a week or so after leaving the treating plant, and it is felt that their reduced insulating properties were due largely to the moisture retained within them. Over 50 of these poles were used and numerous tests made. In figure 9 is plotted the band within which these values fell. This is typical of the spread in the test data obtained in some wood tests. It is pertinent, however, to note that this spread was found to be somewhat greater with the new, moisture-laden poles than was the case with the older and drier specimens. This lower insulation strength of new, undried poles would seem to account for the more frequent flashover and splitting often encountered during the first year's operation of newly creosoted poles, as compared to their performance after several years.

3. Wood Plus Pin Insulators

Figure 10 (*A* and *B*) shows data obtained on combinations of several pin-type insulators, and various lengths



Figures 11A and 11B. Impulse flashover characteristics of pin insulators plus fir crossarms

A—Positive polarity *B*—Negative polarity

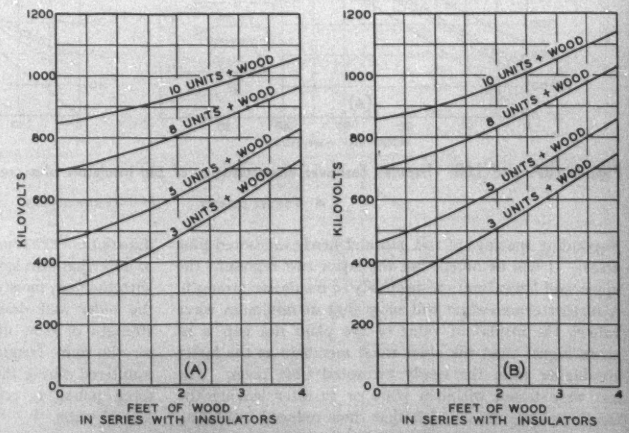
of wood arm. The curves for "wood only" show the insulation supplied by the wood alone. At the zero wood gap points are plotted the corresponding flashover voltages for the insulators only. It will be noted that for lengths of wood arm beyond approximately 10 to 12 inches the curves become straight lines and the insulation strengths increase almost in proportion to the lengths of wood added. In fact a composite plot of data from tests on the several forms of wood and sizes of insulators indicated that the amount of insulation added by the wood is almost proportional to the length of arm regardless of the insulator used or the wood treatment. This is shown in figure 10*C*. In the case of the positive surges the curve slope shows an insulation increment of about 130 kv per foot of wood and for the negative surges about 110 kv per foot, these values representing minimum flashover values.

In figure 11 (*A* and *B*) are given the overvoltage characteristics of pin insulators on wood arms. These curves are derived from data taken on both creosoted and untreated arms as it was found that the wood treatment had comparatively little effect upon the resultant insulation strengths of the arm and insulator combinations tested.

4. Wood Plus Suspension Insulators

The flashover data obtained with suspension insulators on wood arms were analyzed in the same manner as the data on pin insulators. Figure 12 (*A* and *B*) gives the positive and negative flashover voltage of various lengths of fir arms in series with suspension units.

To show the insulation strength added to suspension insulators by wood crossarms the curves of figure 13 were



Figures 12A and 12B. Impulse flashover characteristics of 5-inch by 10-inch suspension insulators plus fir crossarm, minimum flashover

A—Positive polarity *B*—Negative polarity

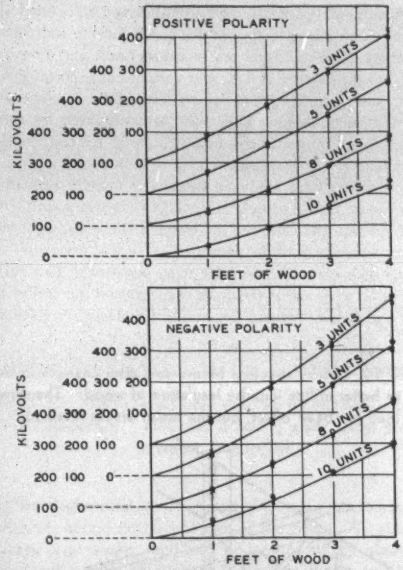


Figure 13. Impulse insulation added to suspension insulators by crossarms—minimum wave values

o—Creosoted pine
x—Untreated and creosoted fir

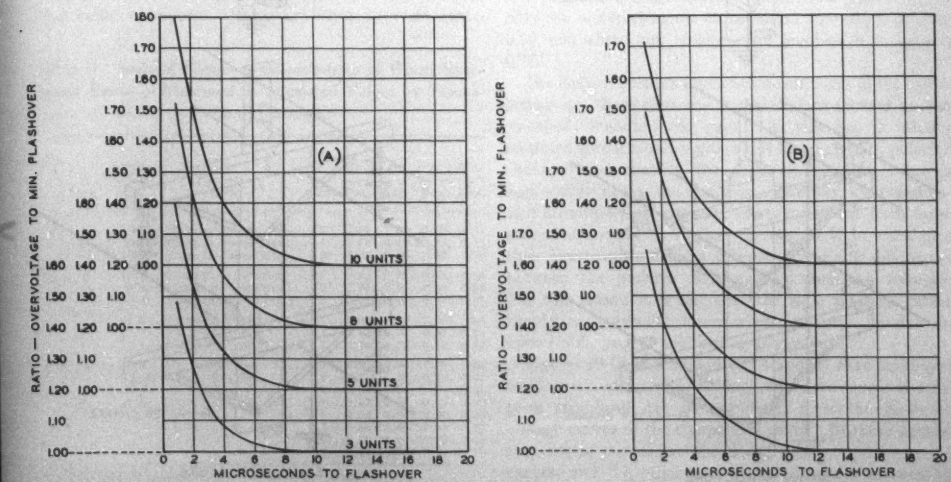
Table I. Comparison of Calculated and Measured Impulse Flashover of 33-Kv Wood Pole (See Figure 15)

Member	Location	Min. Wave Pos.	Min. Wave Neg.	At 2 Ms. Pos.	At 2 Ms. Neg.
Case 1. Phase-to-ground flashover in kv (wood values from figures 4 and 6)					
Insulator	(a)	175	225	236	248
3½" Wood	(b)	65	65	85	85
Sum	(a)(b)	240	290	321	333
Measured	(a)(b)	214	256	300	276
Ratio—Measured/sum		0.89	0.88	0.93	0.83
Case 2. Phase-to-phase flashover—horizontal in kv (wood values from Figures 4 and 6)					
Insulator	(a)	175	225	236	248
3½" Wood	(b)	65	65	85	85
3½" Wood	(c)	65	65	85	85
Insulator	(d)	225	175	248	236
Sum	(a)(b)(c)(d)	530	530	654	654
Measured	(a)(b)(c)(d)	395	420	500	540
Ratio—Measured/sum		0.74	0.79	0.76	0.82
Case 2A. Same as (2) but calculated from combinations of insulation plus wood F.O. in Kv (wood values from figures 10C, 11A, and 11B)					
Insulation and wood	(a)(b)	205	245	265	295
Insulation and wood	(c)(d)	245	205	290	265
Sum	(a)(b)(c)(d)	450	450	560	560
Measured	(a)(b)(c)(d)	395	420	500	540
Ratio—Measured/sum		0.88	0.93	0.89	0.96

developed for both positive and negative impulses. It will be noted that the wood adds more insulation to the shorter string lengths. This is probably due to the voltage distribution between the porcelain and wood insulations in series, as affected by their relative capacities, a point which is being given further study. Another interesting factor developed was that although fir arms have higher flashover values than creosoted pine arms when alone, there seems to be little difference between the two when assembled with insulators. This is clearly indicated in figure 13. The wood values in these curves may be used with suspension units of any of the standard dimensions.

Figures 14A and 14B. Impulse flashover characteristics of suspension insulators plus fir crossarm, one to four feet long

A—Positive polarity
B—Negative polarity



The time-lag characteristics of typical suspension insulators on wood arms from one to four feet long are given in figure 14 (*A* and *B*).

V. Test Results—Complete Structures

Laboratory studies were made of typical transmission line structures in order to determine how well their insulating properties could be calculated from the flashover values of the component parts, these latter values being secured from data curves such as given in the previous figures. Figure 15 shows one of the 33-kv structures, (*A*) being the arrangement before, and (*B*) the arrangement after, construction changes had been made to gain lightning insulation.

Table I gives the data obtained from such an analysis and test. Separate data corresponding to the various parts or members of the structure analyzed and tested are given. In each case the values given for the individual members, such as insulators, wood sections, and air gaps, are from the particular flashover voltage curve corresponding to that member. The stated sums of these values are the arithmetical sums and these are compared by ratio with the actual measured values secured by test on the particular group of members.

In the first case analyzed in table I namely that of a phase-to-ground flashover on a 33-kv insulator and arm combination, the ratios of the sums of the voltages of the separate members to the measured voltage of the combination is seen to be around 0.90 or 90 per cent. This ratio was found to be about the order of magnitude generally obtained in the case where the sum of the flashover voltages

Figure 15. 33-kv structure before and after redesign to increase its impulse strength. Note the use of wood crossarm braces, and the down lead offset from the pole in B

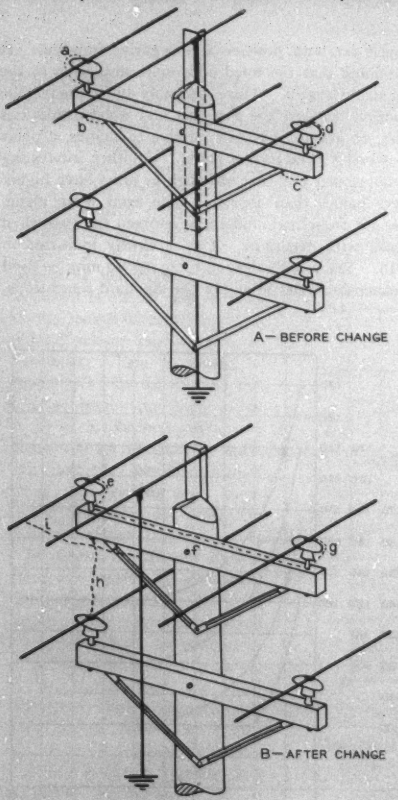


Figure 16. 66-kv structure before and after changes in design to better utilize impulse insulation of wood. The down lead has been offset, but the metal braces retained

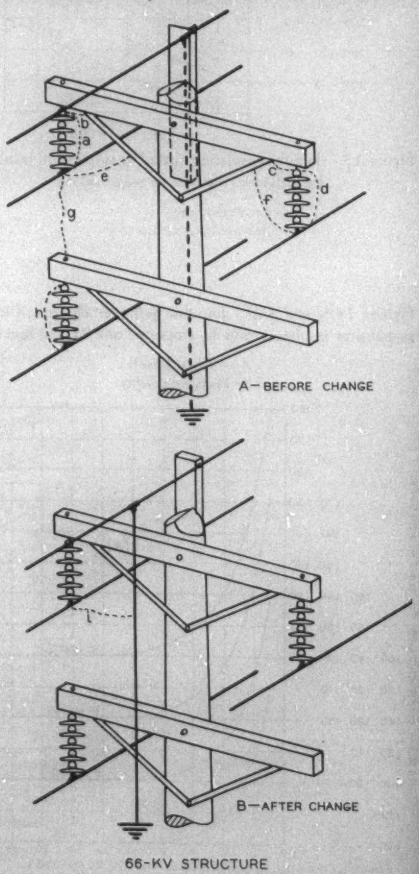


Figure 17. 33-kv wood-pole structure being impulse tested in the laboratory. Flashover is taking place across the top crossarm, line to line

Figure 18. 66-kv wood-pole structure flashing over on laboratory test from conductor to down lead by way of the crossarm, brace, and wood pole

of two single members or groups of members are compared with the actual flashover value of the group. In the case where four single members or groups of members are involved, a ratio of about 0.75 or 75 per cent was found to hold. This is brought out in the second case of table I, where the sums of the individual flashover values of two insulators and two sections of wood are compared with the test values of the combination.

On the other hand if the four members involved, namely, two insulators and two wood sections, are grouped in pairs, each consisting of an insulator and a wood section, values may be chosen from figures 10*C*, 11*A*, and 11*B*. This results in a ratio of approximately 0.90 or 90 per cent as noted for case 2*A*.

In adding these phase-to-phase values, it will be noted that values of opposite polarity are selected for the insulators in each summation. The reason for this is that when one conductor is energized and the other grounded the insulator supporting the energized conductor experiences an electrostatic field of opposite polarity from that of the insulator supporting the grounded conductor. In all tests made phase-to-phase, the down lead was ungrounded.

Figure 16 (*A* and *B*) illustrates the 66-kv structure where the down lead has been moved from the pole to secure increased insulation. Figure 17 shows the 33-kv structure flashing phase-to-phase on test. Figure 18 shows a similar flashover, phase-to-ground, on the 66-kv structure.

In table II the ratios of measured to calculated impulse flashovers for both 33-kv and 66-kv structures are given. It will be noted that where the flashover path is across only one or two elements of insulation the ratio is around 0.90, and where four elements are involved it is around 0.75.

The flashover values taken for the air paths in the calculations are those from the flashover data secured on the so-called "standard rod gap." As this gap is usually mounted rather close to ground, it has a distinct polarity characteristic, that is, the negative flashover value is appreciably above the positive. However, on transmission structures, air gaps are often rather far from large grounded structures, so that there is little to unbalance their electrostatic fields and cause appreciable differences between the positive and negative flashover voltages. For this reason it is felt that the ratio in these tables should be somewhat lower where air gaps involve an appreciable part of the total insulator path.

Figures 19 (*A* and *B*) and 20 (*A* and *B*) were developed to show the accuracy with which volt-time curves of complete structures can be calculated from the flashover voltage curves of the component parts. In these figures, two sets of curves are shown, one the actual measured curves, and the other the estimated curves secured by

Table II. Impulse Flashover Characteristics of Wood Structures; Ratios of Measured to Calculated Values by Summation of Elements

Ref.	Structure Type	Flashover Path	No. of Elements	Min. Wave Pos.	Min. Wave Neg.	At 2 Ms. Pos.	At 2 Ms. Neg.
1	33 kv	Phase to Ground Wire	2	0.89	0.88	0.93	0.83
2	33 kv	Phase to Phase (Hor.)	4	0.74	0.79	0.76	0.82
3	33 kv	Phase to Phase (Hor.)	2*	0.88	0.93	0.89	0.96
4	33 kv	Phase to Phase (Hor.)	4	0.74	0.72	0.84	0.68
5	33 kv	Phase to Phase (Hor.)	2*	0.95	0.93	1.06	0.85
6	33 kv	Phase to Phase (Vert.)	2	0.96	0.85	0.94	0.85
7	33 kv	Ph. to Grd. Wire	1	0.94	0.82	1.02	0.96
8	66 kv	Ph. to Grd. Wire	2	0.87	0.87	0.91	0.91
9	66 kv	Ph. to Ph. (Hor.)	4	0.72	0.72	0.82	0.82
10	66 kv	Ph. to Ph. (Hor.)	2*	0.92	0.92	1.02	1.02
11	66 kv	Ph. to Ph. (Hor.)	2	0.86	0.86	0.87	0.87
12	66 kv	Ph. to Ph. (Vert.)	2	0.89	0.84	1.00	0.91
13	66 kv	Ph. to Grd. Wire	1	0.93	0.88	0.95	0.90
		Average	1	0.94	0.85	0.99	0.93
			2	0.89	0.86	0.93	0.83
			2*	0.92	0.92	0.96	0.95
			4	0.75	0.75	0.81	0.77

* Each element consisted of porcelain and wood or air.

adding component voltages and multiplying by 90 per cent or 75 per cent dependent upon whether two or more figures were added, as discussed above. It will be noted that the two sets of curves agree rather well.

These curves also show the increased impulse strength obtained by the change in construction, that is, by using wood braces and offset down lead on the 33-kv structure, and by offsetting the down lead alone on the 66-kv structure.

A short series of wet tests on wood structures was also made. These tests are not reported here in detail. They apparently indicate, however, that the impulse flashover voltages would be little affected at short-time lags (less than 4 microseconds), but that at long-time lags and at minimum flashover, appreciable reductions might be experienced. In some cases the flashover voltages were decreased 50 per cent. Additional tests are being made on structures under wet conditions to obtain more complete data on their flashover characteristics.

VI. Conclusions

As a result of these tests comprising the application of some 4,000 to 5,000 individual impulse voltages on wood alone and in combination with porcelain, both on individual members and actual structures, the following conclusions seem to be justified:

1. Wood has a definite and sound field of application in supplying insulation against lightning voltages on wood structures such as are commonly used for transmission and distribution circuits.

2. The wood in crossarms can be taken advantage of to supply appreciable impulse insulation on lines using both pin insulators, where the impulse insulation is comparatively low, and on suspension insulators in the higher-voltage ranges where the insulator strings normally have a relatively high insulation strength.

Impulse insulation supplied by wood crossarms in combination with pin insulators is in the order of 110 to 130 kv per foot for minimum waves and somewhat higher for short-time lags.

Tests on individual members as well as complete structures indicate that the flashover path changes as the overvoltage increases. For example, in some cases, flashovers appearing through air for minimum waves will take a path across the wood as the overvoltage increases due to the faster rising volt-time characteristic of the air gap breakdown.

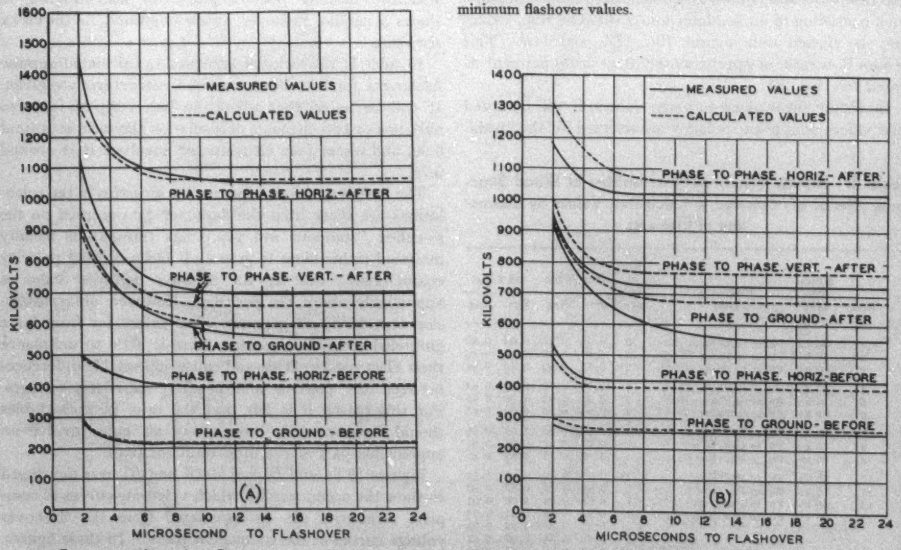
3. The flashover of wood insulating members is affected by the cross-sectional area of the wood, being in general lower the larger the wood section. The factors producing this result are not well understood and the subject should be further investigated.

4. The type of wood commonly used, for example, fir or pine, as used in crossarms, influences the flashover characteristics, fir having slightly higher flashover voltages than pine.

The volt-time characteristics also are different for the two woods, the characteristic for pine being steeper at short-time lags than for fir.

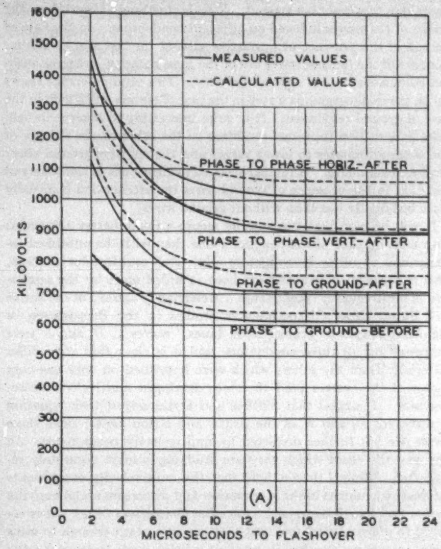
When used in combination with porcelain insulators, however, these different characteristics do not appear to be important.

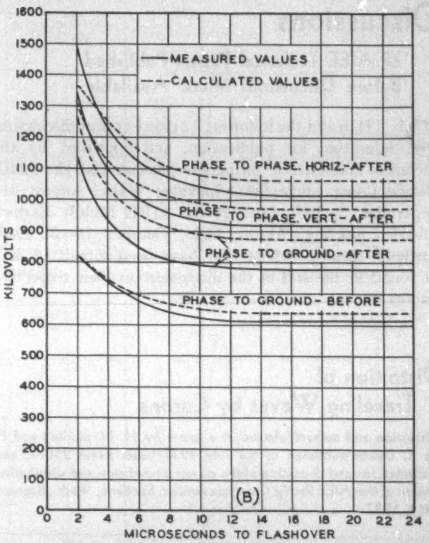
5. The impulse flashover of cedar or aged pine wood poles appears to be very much the same and independent of treatment in lengths up to six feet. For greater lengths, a slight difference is indicated but of relative unimportance in selecting wood-pole material. New creosoted pine poles have considerably less impulse strength at minimum flashover values.



Figures 19A and 19B. Measured and calculated impulse strength of 33-kv wood structures of figure 15

A—Positive polarity *B*—Negative polarity





Figures 20A and 20B. Measured and calculated impulse strength of 66-kv wood structures of figure 16

A—Positive polarity
B—Negative polarity

6. The few tests made on wood under wet conditions indicate that its insulation strength is considerably decreased by the presence of moisture and rain. The preliminary work carried out indicates a reduction in impulse insulation of some 50 per cent under rain conditions. This is another point that needs further investigation.

7. The impulse insulation of wood in structures alone and in combination with porcelain can be calculated with a considerable degree of certainty. It is believed that the data presented here together with reduction factors obtained from tests on actual structures will be helpful in facilitating such calculations in the design of well-balanced wood transmission structures.

8. The data presented above, in the form of groups of curves giving the impulse characteristics of wood under various conditions, greatly amplifies our previous knowledge of the impulse insulating properties of wood, and should be useful in designing wood transmission structures to obtain greater benefit of the wood in supplying impulse insulation to the line. This is particularly important in the medium-voltage transmission lines where structures are inherently of wood, and until recent years, the insulation value of the wood has not been generally appreciated or made use of.

Considerable work still remains to be done in investigating further the impulse insulation strength of wood under various types of treatment, moisture content, and particularly under wet conditions simulating natural rain.

VII. Acknowledgments

The authors received material assistance in these studies from their associates and are particularly desirous of acknowledging the help received from Messrs. I. W. Gross of the American Gas and Electric Company, and C. J. Miller, Jr., of the Ohio Brass Company, in planning the tests and in analyzing the results. Most of the wood materials studied were furnished by The Ohio Power Company.

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Discussions

of AIEE Technical Papers Published Before Discussions Were Available

ON THIS and the following 12 pages appear discussions submitted for publication, and approved by the technical committees, on papers presented at the AIEE Pacific Coast convention, Spokane, Wash., August 31–September 3, 1937; and at the AIEE Middle Eastern District meeting, Akron, Ohio, October 13–15, 1937. Authors' closures, where they have been submitted, will be found at the end of the discussion on their respective papers.

Distortion of Traveling Waves by Corona

Discussion and authors' closure of a paper by H. H. Skilling and P. de K. Dykes published in the July 1937 issue, pages 850–7, and presented for oral discussion at the power transmission and distribution session of the AIEE Pacific Coast convention, Spokane, Wash., September 1, 1937.

L. V. Bewley (General Electric Company, Pittsfield, Mass.): Skilling and Dykes have made a contribution of fundamental importance toward the solution of wave distortion due to corona. In 1931 Skilling developed a formula for the attenuation of the wave, assuming the losses to vary as the excess voltage above the critical corona voltage, but no provision was made in his formula for the associated distortion. In the present paper he has succeeded in formulating an equation for the distortion which occurs on the front of the wave, and which appears to give surprisingly good agreement with the oscillographic record.

I wish to point out, however, that his equation does not take cognizance of the presence of mutually coupled parallel wires and is, in fact, based purely on a single conductor wave. Consequently, the authors' statement under "Other Theories" to the effect that there would be no sharp distinction between their analysis and multivelocity theory is hardly tentable. In the *Conclusions* of my paper "Attenuation and Distortion of Waves," ELECTRICAL ENGINEERING 1933, attenuation and distortion are attributed to three principal causes: (1) multivelocity components, (2) a slippage effect at high voltage levels caused by a reduction in velocity of propagation corresponding to the larger diameters of corona envelope (Boehne's hypothesis), and (3) energy losses. The distortion described by Skilling and Dykes is that due to (2) and (3), and *not* to (1). Three conditions must exist before multivelocity waves can develop: (*a*) There must be a mutually coupled *multiconductor* system, (*b*) the applied waves on this system must be unsymmetrical (for example, the main wave impressed on only one of the conductors), and (*c*) the geometric factors determining the electrostatic field must be *different* than those determining the electromagnetic field, which is possible with a resistive earth or corona. It is therefore manifestly impossible for multivelocity components to be called into existence if only one conductor is present, or if equal waves are simultaneously impressed on all conductors of a system; and yet the Skilling and Dykes distortion is active under both these conditions. I think, therefore, that the crucial test of their formula is to those situations where multivelocities do not exist to mask the results, and thus hinder the segregation of this particular effect.

Contrary to the view expressed by the authors I do not believe that multivelocity components are comparatively negligible at high corona voltages. As shown in my paper referred to, corona calls into existence components of an essentially different character than those due to a resistive ground. This is startlingly revealed by the shape of the waves induced on adjacent conductors. In the case of corona in the presence of a resistive ground the fast and slow components of the induced wave are of the *same* polarity; whereas without corona they are of *opposite* polarity. This vital difference shows up on the oscillograms as a step in the case of corona and a loop in the case of ground resistance. It is quite interesting to observe in field tests a transition from one condition to the other as the voltage of the surge attenuates to lower values and the resistive ground effect begins to dominate. A further piece of evidence lies in the observed fact that in the presence of ground wires the attenuation is initially more but finally less than without ground wires.

It will be seen that the authors secure a much better agreement with tests on their single-conductor line than with the published oscillograms of other investigators who used multiconductor lines. This is because the waves have been retarded more by the separation of multivelocity components. Referring to figure 1 of the Brune and Eaton paper "Experimental Studies in the Propagation of Lightning Surges in Transmission Lines," waves *C*, *D*, and *N* were impressed on all three conductors, and it is clear that they differ materially from the others which were impressed on only one conductor of the system (and therefore developed multivelocity components). I suggest that Skilling and Dykes adjust their equation to waves *C*, *D*, and *N* of the Brune and Eaton paper, since these waves are not further distorted by multivelocity components. In this way the effect which they are studying is more accurately segregated. While I do not hold that the multivelocity components are the chief culprits in the attenuation and distortion accompanying corona (see fourth paragraph under the *Conclusions* of my paper referred to above), yet I feel that they are important enough to mess things up when a worthwhile attempt is being made to segregate the corona *energy loss* factor. There are so many factors responsible for attenuation and distortion (corona, resistive grounds, skin effect, leakage conductance, series resistance) that an investigation of any one of them should endeavor to isolate that one alone as nearly as possible.

Concerning the filling in of the tail of a wave, the authors have repeated the explanation given by Brune and Eaton. They seem inclined to ignore it for "practical cases" which is questionable advice. The wave tail is important in station protection problems, because when the wave impinges on the station capacitance the resultant voltage is very much dependent on the length of the wave, and will be greater the more the wave is filled in. In order to estimate the amount of this filling in I have, on occasion, gone to the other extreme and assumed that all of the space charge returns to the wave as its tail decreases. Thus in an article "Protection of Stations Against Lightning" by Bewley and Rudge, *G. E. Review*, August 1937, a chart is given based on the assumption that the surge attenuates in accordance with the Foust and Menger formula, and that the charge of the wave remains constant. Actually, of course, a large amount of the space charge never returns to the conductor until after the passage of the bulk of the wave (particularly in the case of positive surges), but the assumption errs on the safe side in calculating station voltages.

H. H. Skilling: The authors find themselves in almost complete agreement with the excellent discussion by Mr. Bewley, and wish to offer a reply to the question that he has raised. This regards the relative importance of the effect of "multivelocity components" of a traveling wave and the effect of distortion due to corona, when the crest voltage of the wave is substantially greater than the voltage necessary to produce corona on the line.

The question may be stated as follows: *Is the distortion of a traveling wave due to geometric factors, such as ground, ground wires, and near-by parallel conductors (as considered by Mr. Bewley in the theory of multi-velocity components) negligible when compared to the distortion of the wave due to corona loss, when the crest voltage of the wave is much greater than the corona-forming voltage of the line?*

It is certainly true that this question is not answered by the authors in their paper.

Mr. Bewley offers the following test: "I suggest that Skilling and

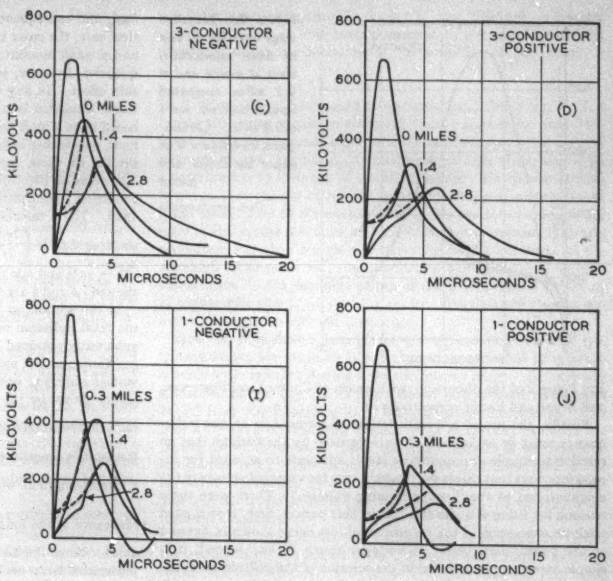


Figure 1. Computed waves compared with oscillograms by Brune and Eaton, waves C and D traveling on one of three conductors and waves I and J on all three

Dash lines computed

Dykes adjust their equations to waves *C*, *D*, and *N* of the Brune and Eaton paper, since these waves are not further distorted by multivelocity components." (Waves *C*, *D*, and *N* were impressed on all three conductors of the experimental transmission line simultaneously, and therefore would not develop multivelocity components.)

In carrying out Mr. Bewley's proposal, the authors went a step farther and compared computed values of waves with every one of the oscillograms reproduced by Brune and Eaton, if comparison was possible and appropriate. Brune and Eaton have sets of oscillograms for the following applied waves: their figures 1 and 2 show waves *A*, *B*, *C*, *D*, *I*, *J*, *K*, *L*, *M*, *N*; and their figure 8 shows a negative wave and a positive wave. Waves *K*, *L*, *M*, and *N* from figure 1 must be eliminated from this discussion because they are at all times below the corona-forming voltage of the line. The positive wave from figure 8 gives no opportunity for useful comparison because only one oscillogram of that wave is given with crest above the corona-forming voltage. There remain, then, waves *A*, *B*, *C*, *D*, *I*, and *J* of figure 1, and the negative wave of figure 8, for comparison with computed results. Of these, waves *C* and *D* were applied to all three conductors of the transmission line simultaneously, while *A*, *B*, *I*, and *J* and the negative wave of figure 8 were applied to only one of the three conductors, the other two conductors being present but not connected to the surge generator.

For comparison, curves from Brune and Eaton's paper are reproduced. Waves *A* and *B* from figures 1 and 2 of the paper by Brune and Eaton appear in figures 8*a* and 8*b*, respectively, of the paper by Skilling and Dykes (page 855). The other waves appear in figures 1 and 2 of the present discussion.

Distortion of all of these waves was computed with the following constants: $n^+ = 2^1/_4$, $n^- = 4$. No distinction was made between the case of waves on one conductor and the case of waves on three conductors. Of course, the corona-forming voltage and the capacitance were different in the two cases, and this was duly taken into account in the computation, but the factor n was unchanged. It will be remembered that the factor n is not merely an adjustable, empirical factor, as explained in the paper (pages 850 and 854). It is understood, however, that there is nothing in the authors' computations that takes into account the effect of near-by conductors on which no surge was applied. Consequently, if the distortion due to "multivelocity components" is a fairly large fraction of the distortion due to corona there should be decidedly better agreement between the computed results and the observed results when the surge was applied to all three conductors in parallel and there were no "multivelocity components."

Whether or not this is the case is purely a matter of judgment. Does it appear that there is better agreement between observed and computed results for waves *C* and *D* in figure 1 of this discussion than there is for waves *I* and *J* of figure 1, or for the wave of figure 2, or the waves of figure 8 of the paper? If the agreement seems about equally satisfactory in all cases (as it does to the authors) then it may be concluded that the distortion due to "multivelocity components" is, in these cases, very small compared to distortion due to simple corona loss, and that the formula (equation 14 of the paper) is reasonably correct despite the presence of near-by conductors.

One interesting detail of figure 2 of this discussion lies in the fact that Brune and Eaton give the form of the wave after it has traveled 2.8 miles, without giving the initial wave form. This figure, then, illustrates the statement in the paper that distortion can be predicted with *any* known form as data—it is not necessary to know the *initial* form. In fact, the initial form can be computed from the form of the wave at a distance of 2.8 miles along the line; this was done, and the result is shown in figure 2. Whether or not the computed initial wave is correct is not known, but it is quite consistent with other initial waves shown by Brune and Eaton. It must be noted, however, that the shape of the initial wave cannot be determined for voltages above the crest of the observed wave.

There is one point of interpretation on which the authors cannot agree with Mr. Bewley. He says, "It will be seen that the authors secure a much better agreement with tests on their single-conductor line than with the published oscillograms of other investigators who used multiconductor lines." The authors must confess that more trouble was encountered in fitting the distortion equation to their own results than to the published oscillograms of others. This is reflected in table I on page 856. Also it is felt that the poorest agreement appears in figure 3, page 852, where comparison is made to experimental results by Dykes; and the best in figure 9 of the paper

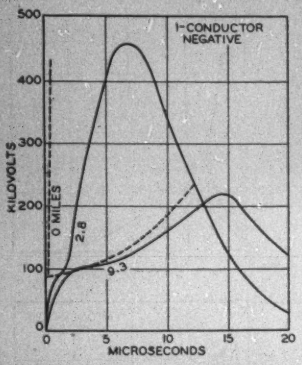


Figure 2. Negative wave traveling on one of three conductors; wave at source and at 9.3 miles computed from observed wave at 2.8 miles. Oscillograms from figure 8 of paper by Brune and Eaton

Dash lines computed

and figure 2 of the discussion, with waves of Conwell and Fortescue, and Brune and Eaton, respectively.

Finally, the use of a quadratic law of corona loss at power frequency must be explained. It is recognized by the authors that no relation so simple as a quadratic law is adequate to account for corona loss, and that this is particularly true for values of voltage in the neighborhood of the "corona-forming voltage." There were three reasons for using a quadratic law in this paper: first, it is a good analytic expression of the experimental loss curve shown in figure 4 of the paper, particularly at voltages above 75 kv; second, it is simple enough to be handled in the solution of the differential equation, equation 11; third, it is generally known (whether or not it is generally accepted) and it can readily be applied to a wide variety of conditions.

Several other expressions for corona loss were tried in the course of the study that led to this paper. At one time it was assumed that the loss was proportional to the first power of voltage above the corona-forming voltage; this described a traveling wave which was reduced at the crest but which maintained a constant slope of front—a result that is manifestly incorrect. Another attempt was based on loss proportional to the 1.6 power of the total voltage: this gave results that were good for high voltages, for it is a good approximation of the corona loss at high voltages, but it did not show a break in the front of the wave at the corona-forming voltage.

If it is possible experimentally to determine the actual corona loss on a line under investigation, that may be done. A true analytical expression can then be fitted to the loss curve, and equation 11 may be rewritten and solved for that special case.

Transmission Lines at Very High Radio Frequencies

Discussion and author's closure of a paper by Lester E. Reukema published in the August 1937 Issue, pages 1002–11, and presented for oral discussion at the communication session of the AIEE Pacific Coast convention, Spokane, Wash., September 2, 1937.

S. A. Schelkunoff (Bell Telephone Laboratories, Inc., New York, N. Y.): In the course of his paper and in the concluding paragraph Professor Reukema states that a shorting disk used to short a coaxial line does not radiate. He further says: "Since such a disk does not radiate power itself, it cannot prevent the radiation of power through it from the current in the line." Thus, according to Professor Reukema, *power is radiated* from a coaxial pair shorted at both ends with conducting disks and energized by a generator somewhere in series with the inner conductor. But in reality, if the outer conductor and the shorting disks are perfect conductors, *there can be no radiation* since the electric field tangential to this outer surface, and consequently the Poynting flux, vanishes. In any practical case, the outer conductor and the shorting disks are not perfect and a small amount of power escapes through them. At high frequencies, however, this power is exceedingly small because of the skin effect. In any case, this is not the radiation with which Professor Reukema is concerned since his calculations of radiation are based upon a tacit assumption that the conductors are perfect. The most convincing argument consists, perhaps, of actual calculations similar to those contained in my paper on "Some Equivalence Theorems of Electromagnetics and Their Application to Radiation Problems," published in the *Bell System Technical Journal*, January 1936. These calculations show that the radiation resistance of the shorting disk is $\left(\frac{2\pi S}{\lambda^2}\right)^2$ ohms, where S is the area of the disk ($S = \pi b^2 - \pi a^2$) and λ is the wave length. It is assumed, of course, that the radii a and b are small compared with the wave length.

In the section on "Radiation Resistance of Parallel-Wire Lines" the total radiation resistance of a circuit comprised of two parts is apparently obtained by Professor Reukema by adding the radiation resistances of the individual parts without taking into account the *mutual* radiation resistances. That this procedure is dangerous is amply shown by the following example. It is well known that the radiation resistance of a short wire of length l is $80\pi^2\left(\frac{l}{\lambda}\right)^2$. Applying Reukema's procedure to two short wires, placed end-to-end to make a wire of length $2l$ we obtain $2 \times 80\pi^2\left(\frac{l}{\lambda}\right)^2$ ohms for the radiation resistance of the longer wire, instead of the correct value $80\pi^2\left(\frac{2l}{\lambda}\right)^2$ ohms. Since the latter figure is twice the former, it is evident that the mutual terms are equal to the radiation self-resistances. Another example is furnished by a coaxial transmission line one-half wave length long, open at both ends, and energized from the center. The radiation resistance of either conductor is about 73 ohms, barring small correction terms depending upon the radius (the radius is supposed to be small compared with λ). If the mutual radiation resistances are disregarded, the radiation resistance of the coaxial pair becomes 146 ohms. In reality the mutual radiation resistance is such that the principal terms in the total radiation resistance cancel, leaving only the small correction terms which depend upon the radii. In general, the complete expression for the flow of energy per unit area is

$$E \times H = (E_1 + E_2) \times (H_1 + H_2) = E_1 \times H_1 + E_1 \times H_2 + E_2 \times H_1 + E_2 \times H_2$$

where E_1, H_1 and E_2, H_2 are the fields produced by the currents in the separate parts of the complete radiating circuit. Evidently the middle terms are the mutual energy terms; they may be either positive or negative. In very special cases, of course, the middle terms may vanish.

C. W. Hansell and **P. S. Carter** (RCA Communications, Inc., Rocky Point, N. Y.): The section of this paper which treats the radiation from concentric lines is of particular interest to us since we have had considerable practical experience with numerous transmitters using concentric lines for frequency stability. We disagree with the author's conclusions concerning radiation from concentric lines. Contrary to the author's conclusion there would be no radiation from a concentric line of perfectly conducting material closed at both ends. In a practical arrangement wherein the transmitter is entirely shielded with copper of ordinary thickness and this shield is made continuous with the outside conductor of a concentric line the radiation is negligible. Both practice and correct theoretical analysis substantiate the truth of these statements.

Reukema cites as an example a quarter-wave line for 60,000,000 cycles per second for which we gave a Q of 20,000 whereas he has calculated the Q to be only 3,420. He states that radiation is 5.6 times the other power losses or 85 per cent of the total power input to the line. According to this statement resonant lines should radiate almost as much of the total input power as dipole antennas

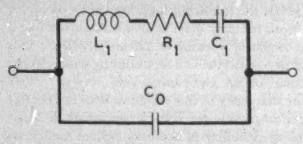


Figure 1

and there should be intense electromagnetic fields in the space surrounding them just as there would be in the space around an antenna. As a matter of fact completely shielded transmitters with resonant-line frequency control, such as those in commercial service on the radio relaying circuits between New York and Philadelphia, operated by RCA Communications, Inc., have so little radiation that a sensitive receiver is required to detect their radiation in the transmitter room. Even this radiation has been shown, by probe tests, to be leaking out over the power leads which are not quite perfectly filtered.

We have some resonant line installations in which power inputs to the resonant lines are on the order of kilowatts but still the electric fields surrounding them are negligible. If we actually radiated 85 per cent of the line input power, as Reukema says we do, we know from experience with unshielded circuits and indoor antennas that the transmitter room would be filled with intense electromagnetic energy by means of which lamps could be lighted without wires and operators would be subjected to great discomfort from high-frequency heating and artificial fever.

As a matter of fact Reukema's conclusions are contrary to common experience with high-frequency shielding. Most radio engineers are so well aware of the effectiveness of shielding that they take it for granted a water-tight metal enclosure completely surrounding any kind of high-frequency electrical circuit, regardless of shape or dimensions, will make the radiation negligible.

To connect up experience with theory let us consider a concentric line made up of perfect conductors which is closed at both ends and includes within it a radio transmitter. The energy generated by the transmitter is stored in the electromagnetic fields existing in the space between the conductors because a perfect conductor can sustain no electric field. In order for energy to be radiated from such a line an electromagnetic wave must penetrate the conductor. However, an electromagnetic wave cannot exist without storage of energy in the electric field and we have just stated that a perfect conductor can sustain no electric field. It therefore follows that passage of electromagnetic waves through the outer conductor and radiation from such a line could take place only by violating the fundamental laws of electromagnetic theory.

The author shows no derivation of the formulas given but, to one who is familiar with such problems, it is apparent that perfect conductors were assumed. Since these equations show very definite and comparatively large amounts of radiation the question naturally arises as to wherein lies the error. The well-known transmission line equations are only approximations which, while sufficient for most engineering purposes, are inadequate for treating the radiation from a concentric line. It is evident that the current distributions assumed in deriving the formulas given were taken from the common transmission line equations. A fundamental analysis of a concentric line indicates that such current distributions can exist only along the central portion of a line many wave lengths long, yet these current distributions have been assumed to hold for lines even shorter than a quarter wave length. Although an exact solution of the wave equation for a finite concentric line having closed ends is exceedingly difficult, if not mathematically impossible, we can state that no distribution of currents within such a system can exist which will produce other than zero electric or magnetic field strengths at *all* positions lying outside the conductors.

An electromagnetic wave will penetrate an imperfect conductor such as copper. However, at the very high radio frequencies under consideration here the attenuation of such a wave is so extremely high that the radiation passing through copper of any thickness ordinarily used would be of an infinitesimal amount in comparison with the quantities under consideration in the formulas of this paper.

W. P. Mason (Bell Telephone Laboratories, Inc., New York, N. Y.): In his interesting paper on radiation from transmission lines Professor Reukema has made some valuable calculations on the effect of radiation on the Q of balanced and concentric lines which should be a contribution to their use as circuit elements. He appears to feel, however, that the use of crystals in the ultrahigh-frequency region is not feasible, for he states that "The Q of a crystal (defined as the ratio of its inertial reactance to its frictional resistance) is inversely proportional to the frequency and assumes such a low value at the ultrahigh frequencies as to be practically worthless for frequency stabilization." He mentions values of the Q of a crystal as 170 at 30 megacycles and 17 at 300 megacycles. Fortunately these statements do not agree with our experience.

Since no published values of the Q's of crystals over wide frequency ranges are available it was thought worth while to measure a number of crystals covering a wide frequency range. Accordingly a number of AT and BT crystals whose fundamental frequencies varied from 800 kilocycles to 20 megacycles were measured. The Q of a crystal is defined with respect to the equivalent circuit of the crystal shown on figure 1. Here the static capacity of the crystal is designated by C_0, while the effect of the motional impedance of the crystal is represented by the series resonant circuit L_1, C_1, and R_1. The Q of the crystal is defined as the ratio $(2\pi f_R L_1)/R_1$ where f_R is the resonant frequency.

At the lower frequencies the method used to measure the Q was the one described in a former paper ("Electric Wave Filters Employing Crystal as Elements," *Bell System Technical Journal*, July 1934, page 431) and shown on figure 2. It consists of measuring the resonant frequency f_R, the antiresonant frequency f_A, the resistance at resonance R, and the static capacitance of the crystal C_0. From these the Q of the crystal can be calculated from the formula

$$Q = \frac{f_R^2/(f_A^2 - f_R^2)}{2\pi f_R C_0 R} = \frac{1}{4\pi R C_0 \Delta} \text{ where } \Delta = f_A - f_R \qquad (1)$$

At higher frequencies the measurement of resistance becomes less reliable. At these frequencies, however, the reading of vacuum-tube voltmeters is satisfactory, so the circuit of figure 2 was modified to that of figure 3, and the resonant and antiresonant frequencies were measured as well as the voltages across the low terminal resistance at resonance and antiresonance. It is readily shown that the Q of the crystal will be given by the formula

$$Q = \frac{f_R}{2\Delta}\sqrt{\frac{V_R}{V_A}} \text{ where } \Delta = f_A - f_R \qquad (2)$$

and V_R and V_A are the voltages across the terminating resistance at the resonant and antiresonant frequencies, respectively. A third method tried was to measure the voltage across the terminating resistance at antiresonance and a few cycles from antiresonance. For this case the Q of the crystal is given by the formula

$$Q = \frac{f_A}{2\Delta}\left[\left(\frac{V_C}{V_A}\right)^2 - 1\right] \qquad (3)$$

where Δ is the difference in frequency between the antiresonance and the frequency for which the voltage V_c is measured. All three of these methods were compared on several crystals and checked within a few per cent.

The measurement of Q for the fundamental frequency for nine

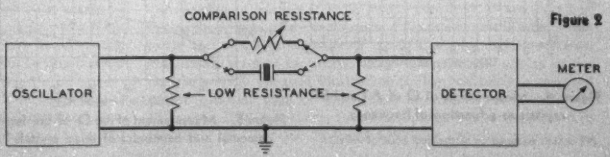


Figure 2

Figure 3

AT and *BT* crystals is shown on figure 4. These crystals were all measured in an air-gap holder in the open air. As can be seen from the figure, there is no significant trend with frequency. The individual difference between crystals is so large that it masks any frequency trend. This difference in Q between shear vibrating crystals is thought to be mainly due to differences in the surface caused by grinding. If the surface layer is taken off by etching or polishing, the Q in general is considerably higher. The shape or size of the crystal does not appear to affect the Q in any significant manner. In any case the Q of crystals at 20 megacycles—which is about as high in frequency as it is feasible to measure the characteristics of crystals with electric oscillators on account of the instability of the electric oscillator— is in the order of 30,000 to 70,000 which is much higher than the figure of 250 which would be obtained using Reukema's data.

Another method for attaining high frequencies with crystals whose thickness can be obtained commercially is to use a mechanical harmonic of a shear vibrating crystal. The electromechanical coupling of such a crystal decreases about inversely as the order of the harmonic, and the ratio of capacities inversely as the square of the harmonic. Nevertheless by using special oscillator circuits it is possible to drive such crystals and have them control the frequency of oscillators. Hence it is of some interest to find how the Q for the successive harmonics varies. For this purpose three crystals were measured having respectively fundamentals of one megacycle, two megacycles, and eight megacycles. The first 15 harmonics of the one-megacycle crystal were measured and the result is shown on curve 1 of figure 5. As can be seen the Q increased with frequency from 93,000 for the fundamental to nearly 400,000 for the fifteenth harmonic. This is what would be expected if most of the dissipation is located in the surface layers, for the harmonic crystal as shown on figure 6 is equivalent to a number of fundamental crystals in combination. If most of the dissipation is located on the two outside layers it is obvious that the effect will be inversely proportional to the number of dividing surfaces or loops and will be considerably smaller for a harmonic crystal than for a fundamental crystal. Crystals 2 and 3 also show its effect of increase in Q with harmonic order but they do not rise to as high limiting values as the first crystal. This is probably due to their lower initial value since the dissipation introduced by the outer faces is higher for them than for the first crystal.

It is concluded from these measurements that after eliminating known dissipative losses in crystals, that there is no evidence of a dependence of Q of a crystal upon frequency.

Professor Reukema, as a result of his opinion on the Q of crystals, seems to feel that crystals will not give frequency stability in the ultrahigh-frequency range as good as can be secured with resonant lines. This again is not in agreement with our experience. Evidence for the use of crystals in stabilizing high-frequency oscillator circuits is furnished by work recently done at Bell Laboratories on a direct crystal-controlled oscillator working at 120 megacycles. This oscillator, which it is hoped to describe in a forthcoming paper, works on the fifteenth harmonic of an eight-megacycle crystal. With plate voltage changes, the frequency of this oscillator does not change more than 0.05 cycles per megacycle per volt change which does not differ much from the voltage stability of ordinary crystal oscillators at low frequencies. Hence we can conclude that crystals in harmonic vibration can be used to control the frequency of ultrashort-wave oscillators and give good stability.

Lester E. Reukema: If my statement regarding the Q of crystals at very high frequencies is responsible for the initiation of the experimental work on the subject reported in Mr. Mason's discussion of my paper, it is fortunate that I made the statement even though it seems to be erroneous. For until this discussion of Mr Mason's appeared, it seemed to be universally accepted by all workers in the field of crystals, at least so far as the published literature is concerned, that the Q of a crystal was inversely proportional to frequency. As proof of this universal acceptance refer to any textbook which even mentions the subject or to the published literature dealing with the equivalent electrical circuit of the crystal. For instance, in Hund's "Phenomena in High-Frequency Systems," combine equation 51, page 311, namely

$$\omega_0 = \frac{540{,}000\,\pi}{b} \text{ or } f_0 = \frac{270{,}000}{b}$$

where b is dimension of the crystal in the direction of vibration and f_0 is the resonant frequency of the crystal, with equation 57, page 313, namely

$$\Delta = \frac{R}{2f_0L} = \frac{0.00202}{b}$$

where Δ is the logarithmic decrement of the crystal, and R and L are the equivalent resistance and inductance of the crystal. This gives

$$Q = \frac{2\pi f_0 L}{R} = \frac{\pi}{\Delta} = \frac{\pi b}{0.00202} = \frac{270{,}000\,\pi}{0.00202 f_0} = \frac{420{,}000{,}000}{f_0}$$

According to this formula, at $f_0 = 30{,}000{,}000$ cycles, $Q = 14$, which is even lower than the value of 170 which I gave. However the decrement depends on the degree of polish of the crystal faces, the way the crystal is held in the holder, and on the air friction, and the constant involved in Hund's equation 57 may readily be decreased to considerably less than the value he gives. In the example given in my paper, I decreased the value of the constant to about one twelfth Hund's value, on the basis of values of Q given in the published literature, thus raising the value of $Q = 14$, as computed from Hund's formula, to my value of 170 at 30,000,000 cycles. The important part of Hund's formula is that it gives Q as inversely proportional to frequency.

I might also quote from Terman's "Radio Engineering," 1932 edition, top of page 265, "...and finally that the effective Q of the

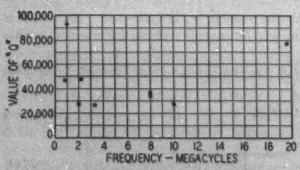


Figure 4. Measurement of Q of AT and BT crystals as a function of frequency

All crystals measured on fundamental mode of vibration

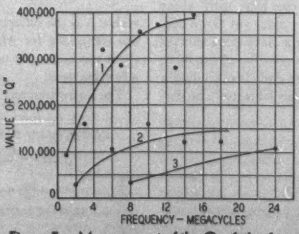


Figure 5. Measurement of the Q of the fundamental and harmonics of three crystals

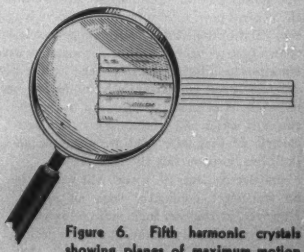


Figure 6. Fifth harmonic crystals showing planes of maximum motion

crystal vibrator varies *inversely* with frequency...." Terman's 1937 edition contains the same statement. This conclusion is reached also in computing Q from the equations for the equivalent R, L, and C of the crystal, as derived by K. S. Van Dyke in IRE *proceedings*, volume 16, 1928, page 743, and as accepted and repeated innumerably since then by the other workers in the field. If Mr. Mason's experimental results are correct, and I have no reason to believe they are not, then universally accepted mathematical analysis of the equivalent electric circuit of the crystal is sadly in need of revision.

Let us consider now the discussion of C. W. Hansell and P. S. Carter. They claim that according to my calculations resonant concentric lines should radiate almost as much of the total input power as dipole antennas. Actually my formulas show that the radiation resistance of their quarter-wave shorted concentric line at 60 megacycles is only 0.01455 ohms, as compared with 73.14 ohms for a dipole antenna. In other words, the concentric line, instead of radiating almost as much energy as a dipole, would radiate only one five-thousandth as much energy as a dipole. For a correctly designed short half-wave concentric line, the radiation resistance is only 1/33,200 that of a dipole. The reason the small amount of energy radiated from a concentric line, used to control the frequency of an oscillator, is not negligible, is that the other losses in the line *are so much smaller*. Of course I did not make the statement that 85 per cent of the power *input* to a concentric line is radiated. It is well known that the loss in concentric lines used to feed power to transmitting antennas is almost negligible, and no one would say that 85 per cent of the input power to such a line was radiated by the line. What I did state was that the loss due to radiation in a particular line used by Carter and Hansell to control the frequency of an ultrashort-wave oscillator, was 5.6 times as great *as the other losses in that line*, and the sum of all the losses is so small that the talk of generating artificial fever in the operators by means of the radiated energy is not valid.

They also state several times that "a perfect conductor can sustain no electric field." The outer surface of a concentric line is a perfect conductor only to the same extent that the surface of a radiating antenna of the same outer diameter is a perfect conductor. Yet everyone knows that voltages of many thousands of volts are set up between the ends of such radiating antennas, as evidenced by the necessity for insulators at the ends. What they should say is that a radiated field, striking such a perfect conductor, cannot set up an electric voltage across it because the resultant movement of electrons in the perfect conductor is such as to exactly neutralize the voltage induced by the field, just as the voltage induced in the secondary winding of a shorted transformer is neutralized by the movement of electrons through the winding itself, leaving zero voltage across the terminals. My computations of energy radiated do not presuppose that a field from *within the concentric line* penetrates the outer conductor, but rather that part of the current in the outer conductor flows on the outer surface, which allows it to radiate just as from any ordinary antenna.

To see that this is so, let us consider first a complete radiating system, entirely enclosed in a copper shield, the shield itself *forming no part of the enclosed circuit*. Any field striking such a shield from within induces in it a voltage which causes a current to flow on the *inner* surface of exactly the value to consume the induced voltage and no energy penetrates the shield (assuming perfect conductivity). Even for ordinary shields the energy which penetrates the shield is infinitesimally small. Since at every point of the shield the flow of electrons on the inner surface exactly neutralizes the voltage induced by the field the voltage difference between any two points on the inside of the shield is zero. Moreover, since no energy can penetrate the shield, the voltage between any two points on the outside of the shield is also zero, so of course no current flows on the outside. In other words, a shield *which forms no part of the enclosed circuit* is exceedingly effective in preventing the radiation of energy through it as amply proven by any number of accurate experimental measurements.

Consider now a concentric line, shorted at both ends and of such length as to be resonant, the length being assumed to extend from a circle halfway between inner and outer conductors on one shorting disk to the corresponding circle on the other shorting disk. Consider a source of high-frequency voltage to be impressed between inner and outer conductors of such frequency as to make the distance between inner and outer conductors an appreciable fraction of a quarter wave length. The field radiated from the inner conductor induces a voltage on the inner surface of the outer tube, causing a current to flow there lagging exactly 180 degrees behind the field which produced it and of such magnitude as to completely reflect the wave back into the inner space. But since the current induced in the outer tube by the field from the inner conductor lags 180° behind the field, it lags *more* than 180 degrees behind the current in the inner conductor, since it requires a finite time for the field to travel from inner conductor to outer tube.

However, the outer tube is acting as the return conductor for the inner tube, and therefore must carry a current *exactly* equal and opposite that carried by the inner tube, if there is to be no voltage set up between the ends of the concentric line. Since the current which flows on the inner surface of the outer tube, due to the field radiated from the inner conductor, is *not exactly equal and opposite* the current on the inner conductor, a slight voltage is set up across the ends of the concentric line, which causes a current to flow on the outer surface of the outer tube, equal to the vector difference between the currents already considered. Of course both radiated and inductive components of the field due to the current on the inner conductor must be considered, in computing the current which flows on the outer surface of the outer tube. When the spacing between inner and outer tubes is very small compared to a quarter wave length, as is the general case except at the ultrashort wave lengths, this outer current is practically infinitesimal. Even at the ultrashort waves, the outer current is so small compared to the current which flows on the inner surface of the tube, that the energy radiated is of the order of 0.01 of 1.0 per cent of that which would be radiated if all the current were on the outside. However, *small as it is, the energy radiated is by no means negligible, compared with the other losses in the concentric line.*

This point has been neglected both by Carter and Hansell and by Schelkunoff, which is the reason that the latter finds a finite radiation resistance from a perfectly conducting shorting disk, whereas my equations show this radiation resistance to be exactly zero. Mr. Schelkunoff's remarks concerning my direct addition of the radiation resistance of a shorted parallel-wire line to the radiation resistance of the shorting bar are perfectly correct. For high accuracy the *mutual* radiation resistance would have to be considered. However, the fact that the line and the shorting bar are perpendicular to each other makes the mutual radiation resistance quite small, compared with the total radiation resistance, and I neglected it because there seems no way to combine it with the other results *for all lengths of line* without making the equations unwieldy. In any case my conclusion that the shorted parallel-wire lines should be brought together at the far end gradually, thus eliminating the necessity for a shorting bar would be in no way changed.

A Review of Radio Interference Investigation

Discussion and authors' closure of a paper by F. E. Sanford and Willard Weise published in the October 1937 issue, pages 1248–52, and presented for oral discussion at the selected subjects session of the AIEE Middle Eastern District meeting, Akron, Ohio, October 13, 1937.

W. C. Osterbrock (University of Cincinnati, Cincinnati, Ohio): The location of sources of radio interference such as are described in this paper is in many cases quite difficult and this is largely due to the fact that faults capable of creating serious interference with radio reception may be entirely insignificant in their effects on the electric service. A good illustration of this possibility is reported in the editorial page of *Electronics*, September 1937, by R. L. Peterson. In this instance, the uncertain contact between turns of the armor on BX cable produced a variable impedance such as re-

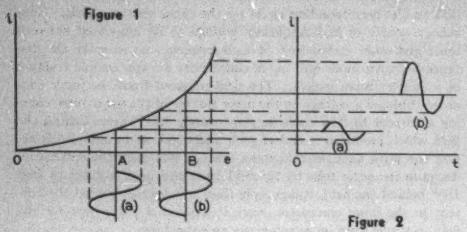


Figure 2

ferred to in the section on "External Cross-Modulation" of the paper, and this gave rise to the effect described, namely background tone from one or more interfering stations. It would seem that the location of such a fault might require, in addition to good measuring technique, a slight touch of genius.

The manner in which cross-modulation is produced by a nonlinear impedance may be considered qualitatively by reference to figure 1, which shows the current in such an impedance as a function of the voltage, and figure 2, which shows current as function of time for two different conditions.

In figure 1, (*a*) represents the desired signal voltage when the interfering signal has a value *OA*, and (*b*) represents the same voltage for an interfering voltage *OB*. The corresponding currents are shown at (*a*) and (*b*) of figure 2, and are seen to be quite different. In the course of modulation the interfering voltage varies from *OA* to *OB*, and the sensitivity of the system to the desired signal is caused to change correspondingly. As a result the modulation of the unwanted station is heard as a more or less distinct background.

The above analysis is not complete, as it ignores the rapid variation of interfering signal during the cycles (*a*) and (*b*). A more satisfactory procedure is to develop the current function into a Taylor's series, and if this is done, it turns out that the third-order term causes a current component to appear *having the same frequency as the desired signal*, but whose amplitude is a function of the interfering signal voltage. The receiver is of course tuned to this frequency in question, and responds as well to this particular component as to the original signal. Incidentally, the cross-modulation term is proportional to the *square* of the interfering signal voltage, and thus every increase in power of a local broadcast transmitter can be expected to produce a flood of new complaints.

As mentioned in the paper, the interference may be transmitted to the receiver by reradiation from the offending conductor, but it may also arrive there via the line cord. Whether it does or not will depend largely upon the effectiveness of the receiver grounding system.

The authors are to be commended for their thorough review of the situation, and their company for its enlightened policy in the investigation of complaints. Many cases have come to my attention of painstaking investigation by their radio squad, even though only a remote possibility existed that the trouble might be due to some fault in the lighting service.

J. J. Smith (General Electric Company, Schenectady, N. Y.): The authors deal with the problem of radio interference from the point of view of a utility whose territory is close to one of the broadcast centers. Under these conditions the radio set users would expect to get good reception. It is interesting to note in table I that 18 per cent of the complaints investigated were due to receiver trouble as compared with 11.5 per cent which were due to the company's distribution lines and equipment. The statement that the number of power cases is only about 25 per cent of what it was in the first years of the investigation work is encouraging. The trend toward greater co-operation between the power company investigations and the radio service men is also an indication that progress is being made.

The thing that is needed now is to carry out studies on a quantitative basis. The authors refer to the results that have been accomplished through inductive co-ordination of power and telephone systems. These results would not have been possible without the quantitative data obtained co-operatively through the joint Subcommittee on development and research of the EEI and Bell Telephone System. To obtain such data, wave-shape surveys have been made on a number of power systems in different parts of the country, coupling coefficients have been measured between typical power and telephone systems, data have been obtained on the characteristics of telephone circuits and apparatus, and many other studies have been made or are in progress.

A similar approach to the problem of radio interference which the paper suggests would involve the collection of data on signal strengths of broadcasting stations and noise levels in different localities, data on coupling between radio receivers and electric circuits in houses, data on characteristics of power apparatus, etc. Such a study is being carried on by the joint co-ordination committee on radio reception of EEI, NEMA, and RMA. The committee has recommended suitable instruments and methods, and issued a report entitled "Methods of Measuring Radio Noise" which is available through the headquarters of the EEI, NEMA, or RMA. This report gives specifications for the instrument recommended for measuring radio noise and the procedure to follow in the use of this instrument. Subcommittees have also been set up for collecting and correlating quantitative data and it would be of great assistance if those who are doing field work like the authors of the paper would obtain more data and report their results in the form suggested by this joint subcommittee.

P. L. Bellaschi (Westinghouse Electric & Manufacturing Company, Sharon, Pa.): Radio noise from power sources presents problems of a complex character but fortunately in practice many of these can be approached and disposed of satisfactorily through relatively simple procedure, as Messrs. Sanford and Weise have indicated in their paper. The fundamental aspect of radio noise remains, on which considerable progress already has been made.

An important contribution to this progress has been made possible by the joint co-ordination committee on radio reception of EEI, NEMA and RMA, in specifying suitable and adequate methods of measuring radio noise. Mention should be made of EEI publication No. *C*-9 or the corresponding NEMA (No. 102) or RMA (No. 13) publications.

The above mentioned technique and methods of measuring radio noise have been applied for a number of years at the East Pittsburgh laboratory of the Westinghouse Electric & Manufacturing Company ("Measuring Radio Interference from High Voltage Apparatus," C. V. Aggers and W. E. Pakala, *The Electrical Journal*, December 1933). Another laboratory, fulfilling the EEI-NEMA-RMA recommendations has recently been installed at the Sharon plant of the same company. Comparison of measurements have been made between these two laboratories to correlate results. For example, when a simple electrode arrangement as a rod to plate was employed the characteristic curves of voltage versus microvolts for the two laboratories are found to come within a few per cent of each other. Even wider variations would be considered good agreement at the present status of the art.

Fundamental investigations always should present room for possible improvement and refinements both in the technique and the methods of measurement. Yet experience has well demonstrated that in the long run much is to be gained through orderly standardization of methods and technique. It is for these reasons that the general application of the methods recommended by EEI-NEMA-RMA hold out promise toward a rapid rationalization of the radio noise problems. As Messrs. Sanford and Weise have clearly stated the complete elimination of all radio interference appears uneconomical, the aim being chiefly to establish permissible levels for electrical apparatus which are reasonable and economically feasible.

F. R. Benedict (nonmember; Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pa.): Short-wave and broadcast program listeners are confronted at one time or another with radio interference which makes reception very unpleasant. Unfortu-

nately, the general public has not been educated in the problems associated with interference and interference producing devices, but only know of it by the interference to their favorite program. Usually this interference is not under the control of the listener and his dissatisfaction is accompanied by a feeling of frustration, which is directed at the world in general. For the past seven years, a group of engineers have been working on the problem of interference and its relation to broadcast reception. This group has been studying the co-ordination of the newer uses of electricity with its older uses for power, light, heat, transportation, and communication, so that the growth of each of these will not be restricted by the requirements of the others. This program is being carried on by the joint committee on radio reception of the Edison Electric Institute, National Electrical Manufacturers Association, and Radio Manufacturers Association. Preferred methods of measurement have been developed and appear in the NEMA publication No. 102. Consideration is also being given to factors in the design of machines and power systems which may affect radio reception. The characteristics of radio receiving sets and the relation of shielding, sensitivity and selectivity to the elimination of radio noise, is also being carefully studied.

The source of radio interference can be determined by the audio characteristics produced in the radio loud speaker. The different types of interference may be classified in two groups, (*a*) uncontrollable interference and (*b*) controllable interference. Under class (*a*) are found atmospherics, i.e., lightning, background static, solar interference, snow and sleet static, etc. Under class (*b*) are found commutating machines, transmission line equipment (such as bushings, pin insulators, transformers, etc.), diathermy machines, sign flashers, auto ignition, etc.

The first class of interference is termed uncontrollable because of the engineer's inability to deal with the source of the noise. It is present at all times, although the amount of trouble it will produce varies considerably with time, weather conditions, and from one locality to another. Radio engineers have done much to improve this condition in modern receivers by increasing selectivity, or in short designing for a high signal to noise ratio. Another aid in eliminating trouble from this class of interference is obtained through increasing the power of broadcast stations and making use of transmitting antennas, which will increase the field strength within the normal coverage area. If the signal strength at the receiving antenna can be increased, the ratio of the signal voltage to the noise voltage appearing on the input of the receiver will be increased and the amount of annoyance caused the listener will be eliminated.

The greatest help for the distant listener would be an ideal receiving antenna system and an increase in broadcast station power to bring up the field strength at the listener's antenna. The problem is not so easily solved. Broadcast stations cannot use unlimited power since allotment of transmitting frequency necessitates more than one station on the same frequency with the possibility of interstation interference. Advances are being made in the use of directional antennas and improvement in broadcast station coverage may be expected in the future.

The progress in elimination of atmospherics has been slow as the static interference seems to have transmitting characteristics over the whole broadcast and short wave spectrum. Various schemes of frequency and amplitude modulation have been advanced for reducing atmospheric disturbances in radio receivers, but these schemes are still in the experimental stages and promise only a partial solution to the problem of uncontrollable interference.

That interference classed as controllable or man-made, has become a serious problem. With electric service increasing daily, the need for some consideration of radio interference problems and their relation to the rapidly growing electrical industry, is very essential. At the present time there are a great many devices in use which produce objectionable interference in nearby radio sets when operated on the supply mains. In the next few years many more will be sold and, in themselves, add measurably to the present problems. In many metropolitan areas, where field strengths are low, the problem is already acute. The interference in such areas, is mainly caused by appliances or other electrical devices common to all electrified households. Vacuum sweepers, food mixers, universal motors, electric razors, electric fans, electric toys and many other devices may come under the category of interfering devices. Of these, those devices classed as commutating machines cause the most radio interference troubles.

It is well known that scientifically designed and properly installed filters may be applied in many cases for the reduction of radio interference from electrical appliances. It may be asked—"Why not apply filters to all household appliances which may produce interference and thereby alleviate all future trouble from such appliances?" In answering such a question satisfactorily, consideration must be given to many factors, which are closely allied with the whole interference problem.

The problem begins in the radio owners' homes and simply stated is "For an appliance with known radio noise output voltage connected to the supply lines of the home, how much noise voltage will be induced in the receiver antenna and ground system?" This can only be determined by experimentally finding the ratio of interference noise measured in the factory to that which may be induced in the antenna when in operation on the home supply lines.

Tests made in homes in the Pittsburgh area indicated that about 50 per cent of the cases had less than 10 per cent of the noise as measured at the factory, induced in the antenna and 75 per cent of the cases had less than 18 per cent of the factory noise induced in the antenna. From actual tests, made with the radio receiver in operation, 5,500 microvolts on the supply lines caused no interference to programs in 50 per cent of the cases. Where the better antenna installations were found, the antenna pickup was less than 2 per cent of the factory noise. Such installations gave no interference to programs with 50,000 microvolts on the supply lines. It was proved conclusively that the coupling of the antenna lead in and ground, with the service wiring is a very important factor in noise reduction.

These tests indicated that a good antenna system is essential if a really successful fight is to be made against radio interference in the home. Unfortunately, the radio distributor is more interested in selling the set than in keeping it sold. Accordingly it has been left pretty much up to the consumer to either buy an antenna installation or put it in himself. The utility which supplies the power to run the set, is very much interested in keeping the set sold, as loss of revenue occurs when the set is not in operation. From the utility standpoint, it is more important that the radio dealer sell the consumer, first a good antenna system and, second, a radio set, for it is to the utility the consumer complains in case of interference. From experience it has been found that the best remedy for interfering household appliances is a modern, scientifically designed and properly installed antenna system.

Where interference from household appliances cannot be reduced by installation of the best antenna possible, filters are usually applied on the electrical circuit of the interfering machine. In applying filters, two types of apparatus installations must be considered; (*a*) apparatus operated with the frame grounded and (*b*) apparatus operated with the frame ungrounded. When the frame is grounded, or ungrounded, the noise can best be reduced by placing capacitors of the proper size and characteristics, from each line to frame. Little noise reduction is obtained by connecting capacitors line to line and may even increase the noise output.

In the grounded case, the line to frame capacitors may be any value as they are connected direct to ground. In the ungrounded case, however, large capacitors cannot be connected to the frame because of the shock hazard. Suitable noise reduction is most effectively obtained by connecting two capacitors in series, line to line, and a third capacitor from the midpoint to the frame. The value of this third capacitor has been a much discussed problem for the past few years. If the value of the frame capacitor is too high the shock is very objectionable. The human body is sensitive to about 500 microamperes, so this capacitor must be held to a very low value —0.005 microfarads or smaller. If the filter is used in damp or humid climates the shock hazard is increased. The most serious problem comes in the possibility of the frame capacitor shorting out or failing. Then the shock hazard may endanger life under moist or wet conditions of the skin. In the case of the grounded machine, which may become accidentally ungrounded,

the shock hazard is also serious, as the capacitors may be 0.1 microfarad or more. If, for any reason, more than one capacitor fails full line voltage may appear on the frame. Then the condition is dangerous to life.

To be an effective remedy for all appliance ills, it is readily seen that all manufacturers would have to filter their devices. Immediately the question arises, "Who shall pay for making the appliances interference free?" It has been stated that with a good antenna system, considerable interference voltage is not objectionable in an appliance. If the filter is compulsory, on many of the cheaper household appliances the filter cost may be a large proportion of the total cost of the article, as, for instance, the 10¢ store variety of egg beater, which sells from 69¢ to $1.00. Addition of a filter to such a cheap article may make the price prohibitive for the quality of the article. Where the cost of the filter is only a very small part of the total cost of the appliance, the problem is simply one of absorbing the cost of the filter in the selling price.

Another complication to the problem is that not all of the appliances of a group produce serious interference. Out of 1,000 high-grade appliances only 1 per cent may cause objectionable interference. There is a probability that not all of this 1 per cent will find their way into locations where interference will cause trouble. The same may be said of cheaper appliances, but the percentage of interference producers per thousand may be much higher. In some cases, a simple change in design may eliminate a part or all of the intereference trouble of a group of appliances.

Mass production of a complete line of filtered appliances is a very involved manufacturing problem. It would require (*a*) redesign of the appliance to include space for a filter, (*b*) new dies, jigs, and tools for each class of appliance, (*c*) standardization of filters for production and renewal replacements, and (*d*) a special organization to design and test the filters and appliances. Such a program could only be reflected in the final cost of the appliance to the consumer.

Where the cost of the filter is a small part of the cost of the appliance, it may be economically feasible to apply filters. In fact, several large manufacturers do filter certain classes of their appliances. While the general interference problem is not helped much by such filtering, it is an asset to the manufacturer as it helps to keep the appliance sold. Such filtering reduces complaints on that manufacturer's equipment and promotes good will, which is the best intangible asset any company can have.

F. E. Sanford and W. R. Weise: Professor Osterbrock has offered a qualitative explanation of external cross modulation. This type of interference can well be made the subject of laboratory experiments and theoretical studies, to the end of obtaining an acceptable explanation, which will lead to solution and elimination. So far this type of interference is not common but it may be expected to increase with increasing signal strengths, which overcome some of the more common types of interference.

Mr. Smith suggests the need of more quantitative analyses of radio interference. Undoubtedly this will help, but we believe that exact measurements are of secondary importance compared to a general recognition of the problems and the value of a co-operative spirit among all of the groups concerned.

In the field of quantitative analyses, apparatus and levels of measurement are essential for the further alleviation of interference caused by appliances. Mr. Benedict has pointed out the present uncertainty in this field. The manufacturers of insulators and other equipment for transmission and distribution line use, have given a great deal of attention to this and as a result the electric utilities can purchase equipment which is inherently "radio interference free." As pointed out in the paper, a similar interest in this subject is in order, on the part of the numerous appliance manufacturers. Many are now following along these lines, but many others apparently are not. In time the public will surely recognize freedom from radio interference possibilities, as a desirable feature of any appliance purchased.

Determination of the permissible level rather than the complete elimination of all radio interference must be the aim in the work to be done. A standardization of methods and technique, as is being attempted by the joint EEI, NEMA, RMA committee, is an important step in the direction, as pointed out by Mr. Bellaschi. Manufacturers who have considered the interference possibilities of their products are to be complimented and encouraged.

In conclusion, we feel that this paper justifies itself to the extent that it serves to further focus attention on the radio interference problems yet to be solved. The discussion, both written and verbal indicated that there is wide interest in the subject.

Analysis of Series Capacitor Application Problems

Discussion and author's closure of a paper by J. W. Butler and C. Concordia published in the August 1937 issue, pages 975–88, and presented for oral discussion at the power transmission and distribution session of the AIEE Pacific Coast convention, Spokane, Wash., September 1, 1937.

E. C. Starr (Oregon State College, Corvallis): The paper by Messrs. Butler and Concordia is a valuable contribution to the field of power transmission. The authors are to be complimented upon the breadth and thoroughness of their analyses of the principal difficulties encountered in the application of series capacitors to transmission circuits.

The series capacitor offers an almost ideal means of improving the voltage regulation of transmission circuits. The action is instantaneous and line reactance, together with the transformer and generator reactances, can effectively be cancelled. The result should be not only that of eliminating the reactance component of system voltage drop but should also be that of improving the steady-state stability limit of the system.

A few series capacitor installations have at first been more or less unsuccessful. These have cast some doubt over the practicability of their use due to one or more of the characteristic troubles, analyzed by the authors, having arisen in their operation. In applications involving large induction- and synchronous-motor loads, where an attempt has been made to completely compensate, or in some cases overcompensate, for line and transformer reactances, serious surging difficulties have arisen. In other applications, where a large part of the load is of resistance character, and in cases where overcompensation of system reactance was not attempted, the success of operation has been complete.

From a very approximate analysis it can be shown that a simple criterion for the successful application of series capacitors to circuits involving large synchronous and induction machinery is to avoid any attempt at complete or overcompensation. That is, the series capacitive reactance in such circuits should not be made equal to or greater than the combined inductive reactance of the line, transformers and generators involved in the particular circuit in question. This is a very simple criterion and no attempt will be made at this time to carry it to a more exact solution. In some cases it will be objectionable because it does not permit of the complete cancellation of system reactance or in the effective compensation for both resistance and reactance as is possible under some limited conditions.

Reference to figure 1 of this discussion will bring out two interesting features. It will be noted that for any normal load current, I, the sending-end voltage, E_1, is ahead, in phase position, of the re-

E_1 = Sending-end voltage (E_1')
E_2 = Receiving-end voltage
I = Line current
θ = Voltage angle between ends of line (θ')
R = Line resistance
X_L = Line reactance (inductive)
X_C = Series capacitor reactance

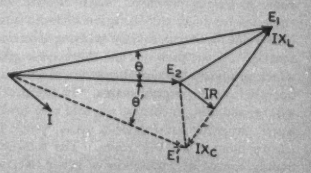


Figure 1. Simple transmission-line diagram

ceiving-end voltage, E_2, by the angle θ. Any increase in the load current, I, is accompanied by an increase in the angle θ, and up to a certain limit the system is stable. If a series capacitor is introduced in the system with capacitive reactance greater than the system inductive reactance, then the dotted line diagram will apply. It will be observed that no change has taken place in the system resistance drop, IR, but that the sending-end voltage, E_1', is smaller in magnitude when compared to E_2 than previously. This indicates the desired improvement in system voltage regulation. It will be noted, however, that the sending-end voltage, E_1', now *lags* the receiving-end voltage, E_2, by the angle θ', and any increase in the load current, I, will cause a further lag of E_1' behind E_2. This means then that if we assume E_1' to be supplied by an infinite bus or by a generator of relatively large rotational inertia, the receiving-end voltage, E_2, will be governed in phase position by the line current, I_1, an increasing current meaning an *advancing* phase position.

This condition is inherently one of instability. If, for example, the load consists of a synchronous motor and a sudden increase in delivered torque should occur, then the load current, I, would increase correspondingly and the terminal voltage, E_2, would advance somewhat in phase. This momentary advance of E_2 would tend to accelerate the rotor of the motor and again increase the current drawn by the motor from the system. This further increase of current would tend, again, to increase the angle θ'. However, as soon as the rotor had accelerated to accommodate the new phase position of the terminal voltage, the current would drop off somewhat, allowing the phase of E_2 to drop back. The rotor would then drop back in phase position and the current momentarily would decrease. As soon as the rotor had reached its normal load angle, the current would have returned to normal and would again be changing in the upward direction, starting to repeat the cycle of oscillation just described. An unstable surging condition is thus established which involves the complete mechanical as well as electrical system.

The same general analysis can be applied to an induction-motor load. In that case, a suddenly increasing load produces an increased slip which in turn increases the line current and causes the phase of its terminal voltage to advance momentarily. This advance in terminal voltage is the equivalent of a momentary increase in frequency resulting in increased instantaneous slip and hence in a further increase of line current. The rotor then tends to accelerate under the influence of increased current, and thus again starts the oscillation described above.

A very crude analogy is the case of a differential-compound motor driving a cumulative-compound d-c generator. An increase in load on the generator tends to increase slightly the speed of the motor which immediately increases the voltage of the generator and automatically causes it to deliver more load. Such a system, when adjusted for a small degree of overcompounding, will tend to oscillate and surge rather badly. If, however, the overcompounding is excessive, particularly in the case of the motor, the system will surge beyond control.

It can be said in general that, so long as the receiving-end voltage of an electrical system tends to *fall back* in phase with respect to the sending end with increase of load, any oscillations set up externally will be subjected to a definite decrement due to system resistance and machine friction, and the operation will be stable up to the limit of the system. If, however, the receiving-end voltage tends to *advance* in phase with respect to the sending end with increase of load, the system is inherently unstable and a surging condition can develop when rotating equipment is involved.

In most practical systems, particularly those involving a fairly large percentage of resistive loading, a small negative angle will give rise to no difficulties. Hence it is possible to compensate for all, or nearly all, of the system reactance by means of series capacitors without introducing any abnormal operating conditions. However, if large rotating machines are involved in the load, it is not advisable to overcompensate for the system reactance in order to obtain an idealized voltage-regulation condition.

In designing a series-capacitor installation, the load should be carefully analyzed from the standpoint of size and types of rotating machines involved and the power factors encountered. Where large machines are involved in the load, the capacitive reactance should be limited to a value which will not cause the terminal voltage of the machines to advance with respect to the sending-end voltage more than a few per cent of the normal load angle of the machines. It is realized that the voltage-regulation improvement to be obtained by the application of series capacitors is limited by these conditions, but a very large improvement can be produced by their use and further applications should be greatly encouraged.

J. W. Butler and C. Concordia: We wish to thank Professor Starr for his remarks and explanation of the phenomena of self-excitation on the basis of a simple vector diagram. We feel however that in general it will not be feasible to compensate to as great an extent as is indicated by his criterion. As brought out in the paper, one cannot compensate for the total effective steady-state system reactance; even the short circuit or transient reactance can usually be only partly compensated, perhaps half-way compensated. Figures 10 and 12 illustrate this point and show the limits for a particular set of system constants.

Relay Operation During System Oscillations

Author's closing discussion of a paper published in the July 1937 issue, pages 823–32, and presented for oral discussion at the development of protective equipment session of the Pacific Coast convention, Spokane, Wash., August 31, 1937. Other discussion of this paper appeared in the December 1937 issue, pages 1513–14.

C. R. Mason: Mr. Neher has described an extremely valuable method for studying relay operations under abnormal system conditions. His suggestion for applying that method to the problems of this paper merits further consideration. By this method one can determine the operating tendency of various relays quickly, accurately, and with a minimum amount of calculation if he has the conception of the elements of the problem which the paper attempts to provide.

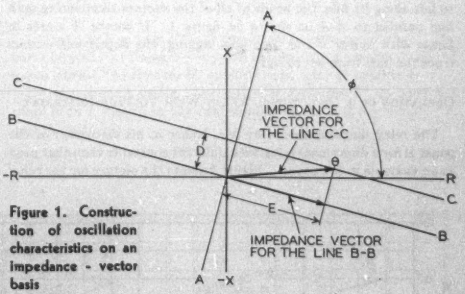


Figure 1. Construction of oscillation characteristics on an impedance - vector basis

Characteristics of a System Oscillation

The relations of current, voltage, and the angle between them can be conveniently represented on a two-dimensional picture by showing the ratio of the voltage to the current vectorially. Consider figure 1. Lay out the resistance and reactance axes to the same scale and draw the line A-A through the origin at the system phase angle ϕ to the resistance axis. Draw the line B-B through the origin perpendicular to A-A. The line B-B applies to the impedance center of the system. At that point the current is always at the same angle to the voltage regardless of change in the displacement angle θ. The impedance vector will always lie on this line, terminating at the dis-

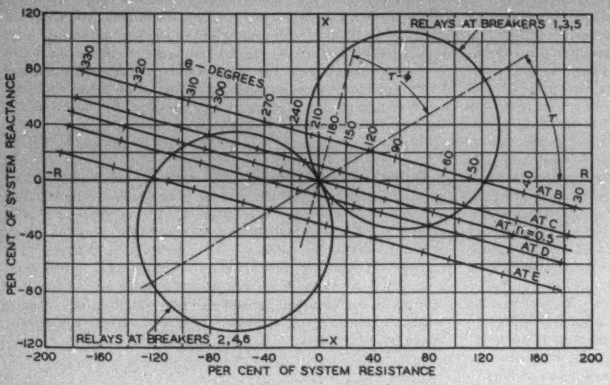


Figure 2. Voltage-restrained directional relay operating characteristics combined with the oscillation characteristics to show relay operation

tance E to the right of the origin for any angle θ less than 180 degrees according to the relation $E = 50 \cot (\theta/2)$ where E is expressed as a percentage of the total system impedance. When θ exceeds 180 degrees, E will be measured to the left of the origin.

For some other point in the system toward the end, which in the paper was labeled "source A," the line C-C will apply. This line is parallel to the line B-B and at a distance D which is the per cent of the total system impedance that the point is from the impedance center of the system. For another point at the other side of the impedance center, the parallel line should be drawn on the other side of B-B.

Having determined θ for desired values of E or vice versa, according to the relation given for the impedance center line B-B, this same E and θ will apply for any other line if measured from the intersection of A-A and that line. In other words, as θ increases from zero, the head of the impedance vector for each location will move from right to left along its line, the heads of all of the vectors terminating on a line parallel to A-A as shown on figure 1. If source A starts in phase with source F and then goes lagging, the impedance vectors trace the lines from left to right.

Operation of a Directional Relay With Voltage Restraint

The relay diagram shown by Mr. Neher in his discussion of the paper is for a directional relay with different constants than that used as an example in the paper. Figure 2 shows the picture for the relay assumed in the paper having a three-phase minimum pick-up current of 7.0 amperes at 115 volts at its angle of maximum torque. The impedance pick-up of the relay at its maximum torque angle is therefore $V_A/7$. Since the system impedance is $2V_A/20$ according to the assumptions used, the relays' impedance pick-up is 10/7, or 143 per cent, of the system impedance at the angle of maximum torque. The relay circle is shown according to Mr. Neher's methods with its center on a line through the origin at an angle $(\tau - \phi)$ from the line A-A of figure 1, or at the angle τ from the R-axis. The diameter of the circle is 143 per cent of the total system impedance as previously determined.

Two circles are shown to account for the fact that the relays at breakers 2, 4, and 6 face in a direction opposite to the relays at breakers 1, 3, and 5.

For values of θ for which the oscillation line lies within the circle, the relay will operate to close its tripping contacts. If figure 2 is used to determine the point at which the relay changes its direction of torque, it will be noticed that slight errors in the curves of the paper are exposed. These curves were drawn from calculated data using the formulas of the paper, and during the process some error was introduced. A careful recheck of these calculations show that the errors are in the calculations and not in the formulas themselves. The fact that such a quick and easy check is possible using Mr. Neher's methods further emphasizes their value.

Figure 3 shows the circles for the voltage restrained directional unit of an actual distance relay which has a minimum pick-up ad-

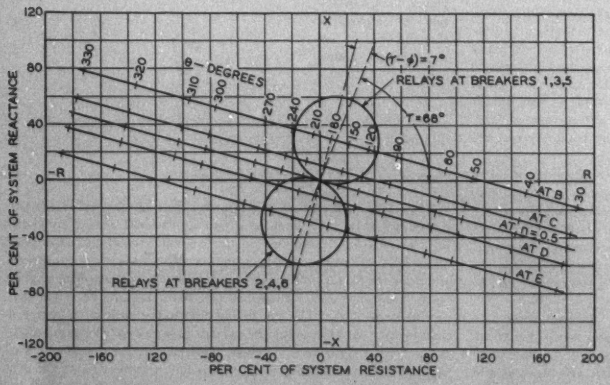


Figure 3. Combined oscillation and relay characteristics for an actual distance relay starting-element

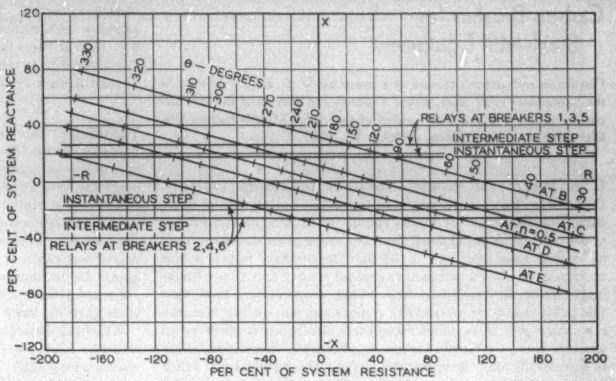


Figure 4. Reactance element operating characteristics combined with the oscillation characteristics to show relay operation

justable to 16 amperes at rated voltage and at its angle of maximum torque (68 degrees). The diameter of this circle is thus seen to be 10/16 or 62.5 per cent of the system impedance; and $(\tau - \phi) = 7$ degrees.

Operation of a Reactance Relay

In figure 4 the operating characteristics of a reactance element adjusted as assumed in the paper are combined with the oscillation impedance characteristics. The operating characteristics of the reactance element are perpendicular to the X axis and intersect it at a distance from the origin which is the per cent of the total system impedance below which the element is adjusted to operate. The element operates to close its tripping contacts when the oscillation impedance vector terminates on the origin side of the relay characteristic. Here, as in the case of the voltage restrained directional relay, the characteristics for relays which face in opposite directions are drawn on opposite sides of the origin. These curves give a very accurate check of the curves in the paper.

Operation of an Impedance Relay

The characteristics of the impedance relay used in the paper are drawn in figure 5, together with the oscillation impedance characteristics. The radius of each curve is the per cent of the total system impedance below which the relay will operate. When the oscillation impedance vector falls inside of a circle the relay operates to close its tripping contacts.

Other Types of Relays

The characteristic of a directional relay without voltage restraint will be a straight line through the origin at right angles to the τ axis shown on figure 2. All oscillation impedance vectors to the right of this characteristic will cause the relays at breakers 1, 3, and 5 to close their tripping contacts; all impedance vectors to the left of the characteristic will cause the relays at breakers 2, 4, and 6 to close their tripping contacts.

The characteristics of single-quantity relays such as overcurrent, and undervoltage types cannot be shown on the diagrams, but their operation is easily determined otherwise.

Errata

In figure 12 *b* on page 828 the curves are incorrectly labeled. The curve labeled "At Breaker 4" applies to the relay at breaker 3 and the curve labeled "At Breaker 3" applies to the relay at breaker 4.

In the appendix under "Derivation of Equation 7" on page 832 there is an I missing in the denominator of the first expression. It should read:

$$Z = V/I$$

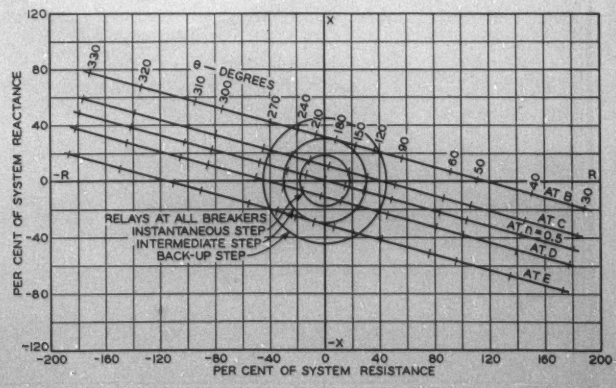


Figure 5. Impedance relay operating characteristics combined with the oscillation characteristics to show relay operation

Carbon Brushes for Steel-Mill Equipment

Discussion and author's closure of a paper by W. C. Kalb published in the September 1937 issue, pages 1165–8, and presented for oral discussion at the iron and steel session of the AIEE Middle Eastern District meeting, Akron, Ohio, October 15, 1937.

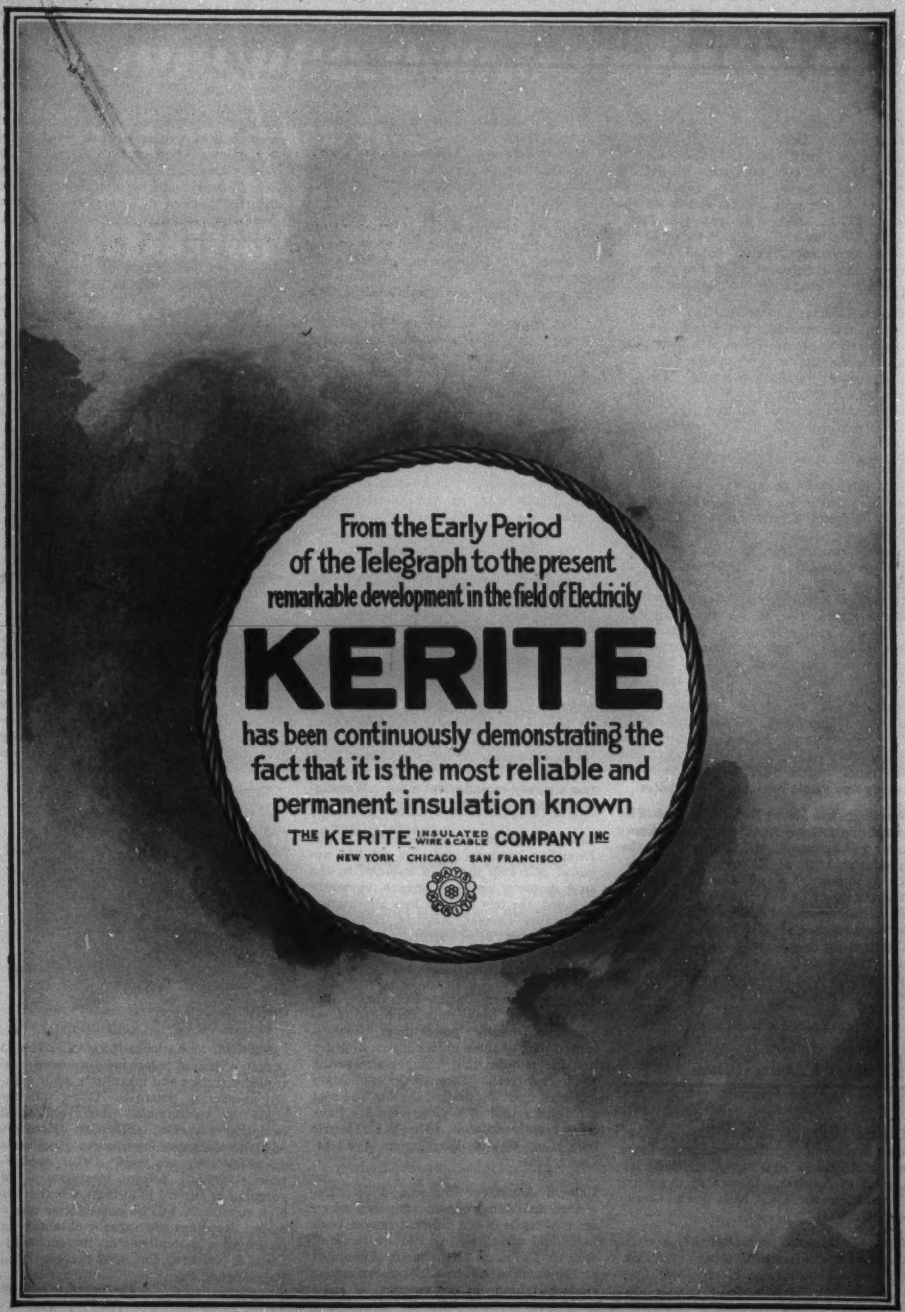
L. E. Miller (The Reliance Electric & Engineering Company, Cleveland, Ohio): I am very glad to see Mr. Kalb bring out in his paper the fact that the same type of brush may be satisfactory under one certain set of conditions, but under other conditions may be entirely unsatisfactory. I feel that the corollary to this is that no type of brush is a satisfactory cure-all for any and all conditions under which the brush may be required to operate. I think that this point should be particularly emphasized, since it has been my experience that often times some particular brush is given to an operator to cure a certain specific set of conditions, and does its job so successfully that the operator desires to use this particular brush for every and all kinds of conditions. The result is many misapplications, causing endless difficulty, expense, and dissatisfaction.

Mr. Kalb, in speaking from notes, quoted from Doctor Glass's paper which occurred in an earlier issue of the *Iron and Steel Engineer*. While Mr. Kalb did not mention in his talk, I believe that Doctor Glass brings out the idea that the film on the commutator which gives the glossy chocolate-brown surface so desired, is a form of oxide in copper. This film, as a rule, is only produced after considerable operation of any particular machine. I would like to ask Mr. Kalb if there has been any experimental work done with the idea of producing this film quickly in any other way than the usual method of operating the machine.

W. C. Kalb: In reply to Mr. Miller's question, it is mentioned in the paper by Doctor Glass, to which reference is made, that the application of methyl alcohol as a reducing agent on a test commutator, operating with lampblack base brushes at an interface temperature of 125 degree centigrade caused the coefficient of friction to rise to 0.5. The application of hydrogen peroxide immediately brought the coefficient of friction down to 0.13, the normal friction, at 125 degree centigrade, of the grade being tested. In applying these reagents the brushes were lifted from the commutator and excess of the reagent was removed before replacing the brushes. Repeated trials gave the same results.

While this laboratory test indicates that a beneficial oxide film might be formed by the application of an oxidizing reagent to the commutator surface, I do not know of any instance where this plan has been tried in actual service.

Formation of oxide film can also be accelerated by the application of external heat to the commutator surface. It might be feasible for the electrical manufacturer to use this means for developing a commutator surface of the desired character before the machine leaves the factory, but the method does not seem well adapted to use in the field.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Industrial Notes

General Electric Orders Decrease.—Orders received by General Electric Company during the fourth quarter of 1937 amounted to $73,997,063 compared with $84,857,181 in the same period of 1936, a decrease of almost 13 per cent. Total orders for the year, $379,273,619, compared with $296,748,219 during 1936, an increase of 28 per cent. President Swope stated that in every major department of the company orders were greater in 1937 than in 1936.

Cutler-Hammer Forms Canadian Company.—Cutler-Hammer, Inc., of Milwaukee, has organized Canadian Cutler-Hammer, Limited for the purpose of manufacturing motor and control products for the Canadian market. The company will be a subsidiary of the Amalgamated Electric Corporation Limited which will provide manufacturing facilitics. The headquarters will be 384 Pape Ave., Toronto 6, Canada.

Allis-Chalmers Promotions.—According to a recent announcement, the Allis-Chalmers Mfg. Company's publicity department for power, electrical and industrial machinery now has two sections, effective January 15. George Callos has been appointed assistant manager in charge of sales promotion embracing advertising, bulletins, exhibitions, house organs, etc. A. K. Birch has been appointed assistant manager in charge of market analysis, sales organization service embracing price books, data and sales information, and the distribution of literature.

New Name for Tape Company.—The Revolite Corporation, of New Brunswick, N. J., has changed its name to Industrial Tape Corporation. Among its products are tapes with flexible Bakelite coatings widely applicable for electrical purposes.

Westinghouse Moves Radio Division.—The radio division of the Westinghouse Company will be moved to Baltimore from the present location at Chicopee Falls, Mass. The company has purchased a modern manufacturing plant at Wilkins Avenue and Catherine Street. Plans have been made for the erection of an office building adjacent. Construction is under way and it is expected that the transfer of equipment and employees and their families will be completed within six months.

Trade Literature

Theatre Lighting.—Bulletin, 60 pp. Presents in a comprehensive manner new ideas and methods in lighting, particularly as applied to theatres. Illustrated in colors. General Electric Co., Nela Park, Cleveland, O.

Fans.—Catalog, 28 pp. Describes a complete new line of fans of all types; prices are included. The Emerson Electric Mfg. Co., St. Louis, Mo.

Time Switches.—Bulletin, 4 pp. Describes several types of new synchronous, self-starting and hand wound automatic time switches recently introduced by the manufacturer. Diebold Safe & Lock Co., Canton, O.

Radio-Proof Pintype Insulators.—Bulletin 637-H, 2 pp. Describes and gives catalog information on Silentype copper coated and aluminum coated radio interference-free pintypes. Ohio Brass Co., Mansfield, O.

Metal-Enclosed Switchgear.—Bulletin 66, 40 pp. Describes metal-clad switchgear, cubicle switchgear, switch houses and switchboards. Profusely illustrated; includes connection diagrams and dimensions. Delta-Star Electric Co., 2400 Block, Fulton St., Chicago, Ill.

Entrance Connectors.—Bulletin 204, 4 pp. Describes a new service entrance connector for house entrances and all small solderless wire connections. A new parallel clamp connector is also described as well as hot line clamps and wire clips. W. N. Matthews Corporation, St. Louis, Mo.

Pyrometers.—Catalog 1101D, 32 pp. Describes indicating, recording and controlling pyrometers and resistance thermometers, which utilize a phototube, mirror galvanometer and a beam of light. C. J. Tagliabue Mfg. Co., Park and Nostrand Aves., Brooklyn, N. Y

Mercury Lighting.—Bulletin F-8409, 4 pp. Describes applications of high intensity mercury vapor lighting in industrial plants. Illustrates a complete line of equipment and accessories for both mercury and combination mercury-incandescent units. Westinghouse Electric & Mfg. Co., Cleveland, O.

Separator Magnets.—Bulletin 910, 8 pp. Describes separator magnets for the removal of tramp iron. In addition to the large diameter circular magnets previously included, the new bulletin lists information on smaller circular magnets, rectangular magnets and other special types. The Electric Controller & Mfg. Co., 2700 E. 79th St., Cleveland, O.

Rectifier Power Units.—Bulletin, 4 pp. Describes new, heavy duty, copper sulphite-magnesium rectifier power units. The essential part of these units consists of a dry metallic rectifier that changes alternating to direct current. Through the application of forced draft ventilation the size and cost of a power unit of a given capacity have been greatly reduced. The B-L Electric Mfg. Co., 19th & Washington Ave., St. Louis, Mo.

Clip-On Ammeter.—Bulletin, 4 pp. Describes dual range clip-on ammeters which are now made in ten different ranges, each individual meter having two distinct full scales. The range of the meter is changed at the touch of a switch. Applications include instantaneous measurement of loads on electrical equipment without opening the circuit. Ferranti Electric, Inc., 30 Rockefeller Plaza, New York City.

Arc Welding.—Bulletin 420, 32 pp. Intended as an aid in applying arc welding to the design of machines, the new bulletin sets forth the experiences of many manufacturers who have re-designed their products for arc welding construction. Of particular interest are illustrations of products as they were formerly built by some other method and their modern arc welded counterparts. Profusely illustrated. The Lincoln Electric Co., Cleveland, Ohio.

Industrial Capacitors.—Manual. Includes ratings, required capacities, power factors and other engineering and servicing aspects of motor-starting capacitors. Simple self-calculating charts are provided for figuring necessary mathematical problems. Five pages of electrolytic and oil-filled capacitor listings cover the requirements of all standard capacitor starting motors, including motor manufacturer's part number, Aerovox catalog number, capacity, voltage, dimensions, list price, etc. Aerovox Corporation, 70 Washington St., Brooklyn, N. Y.

New Products

Thermionic Amplifier.—Bringing high sensitivity to potential measurements in high resistance circuits, this new Thermionic Amplifier, drawing a negligible current, adapts any potentiometer of suitable range to the measurement of glass electrode potentials. It is also useful for measuring potentials encountered in polarization

studies. In this application it is possible to supply a limited polarizing current of controlled direction and magnitude while actually measuring potential. Other uses include the measurement of corrosion and oxidation-reduction potentials. Resistors of high values can be measured at voltages at which they are used. Other applications, involving precise measurement of potential or current in circuits of extremely high resistance, will be apparent to many users. Readings are rapidly obtained by the routine potentiometer measurement. Leeds & Northrup Co., 4962 Stenton Ave., Philadelphia, Pa.

Continued on page 10

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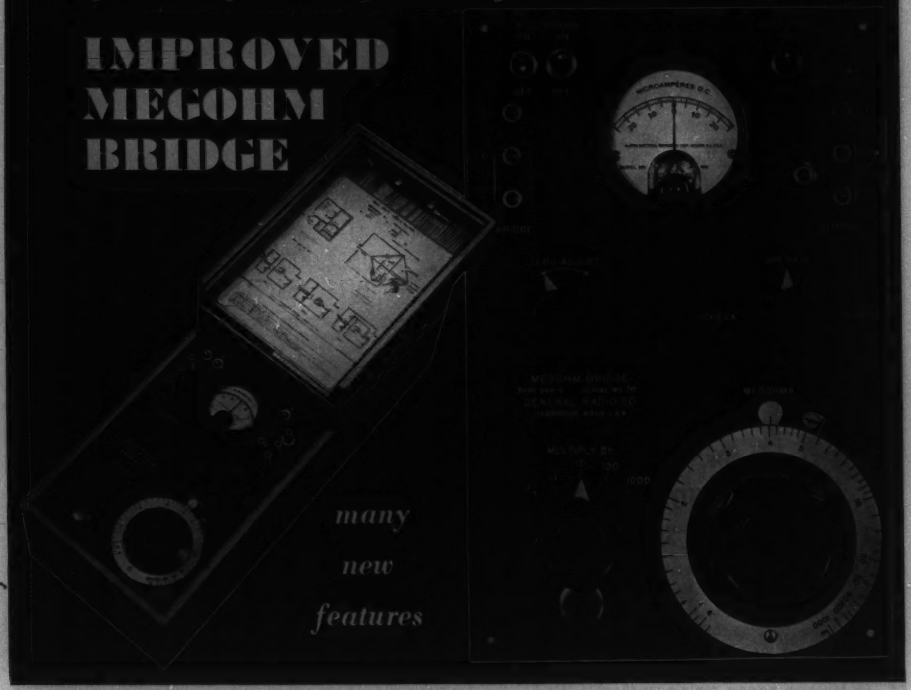

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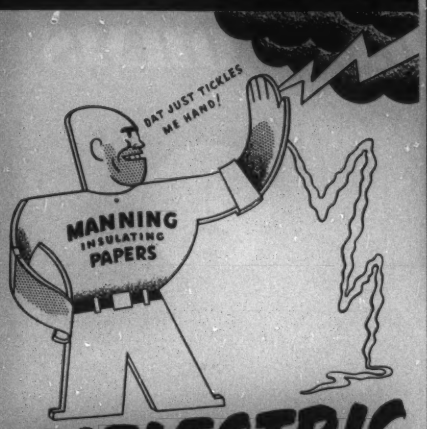

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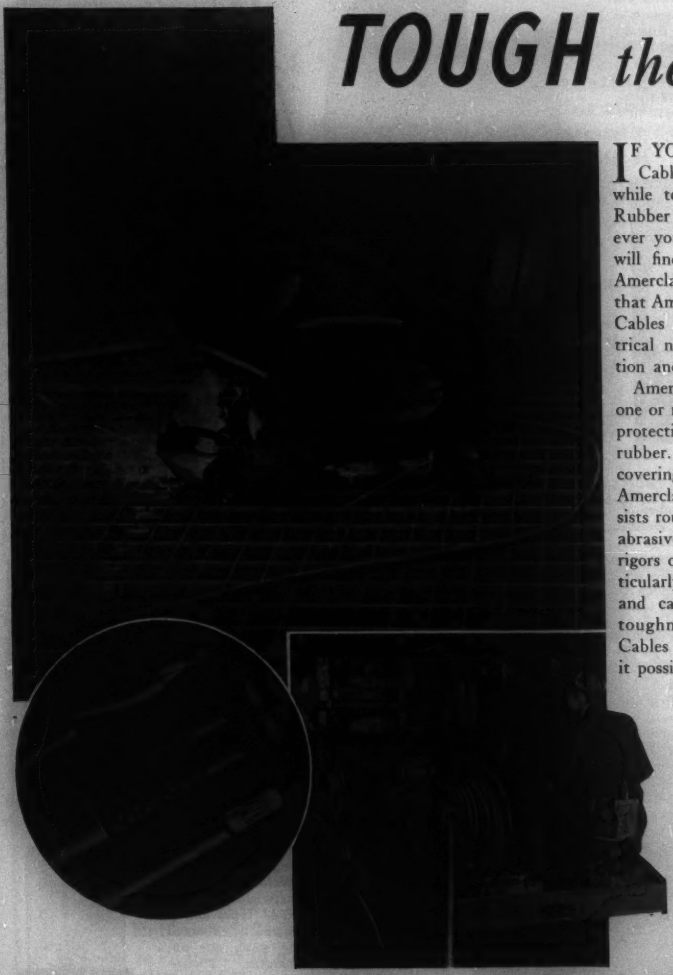

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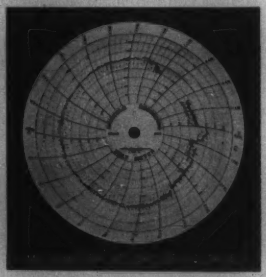
UNITED STATES STEEL

New Products

Continued from page 8

Telemetering Electrical Units.—Electrical units such as volts, amperes and watts, are now accurately measured and transmitted to a remote point by means of Bristol's Metameter. New features included in the design of these instruments have made it practical to apply this system of telemetering to electrical measurements, using standard measuring elements. They have now been adapted to measuring and telemetering electrical measurements of all magnitudes—



from millivoltages to the totalized power output of power plants. The principle involved has been used for a number of years by the Bristol Company, of Waterbury, Conn., in transmitting readings of pressure, temperature flow, mechanical motion, etc., from a transmitter at the point of measurement to a receiver, which is a recording or indicating instrument at some distance away—a few feet or many miles.

Low Voltage Generator Sets.—The Hanson-Van Winkle-Munning Co., Matawan, N. J., recently completed the first two units of an order for eight motor generator sets to be used in the anodic treatment of aluminum parts. These sets are unusual in that they are larger than sets ordinarily used in the past and are equipped with automatic control devices designed to vary generator voltage through a predetermined cycle of values as required for the specified treatment of a batch of aluminum parts. The normal rating of the generators is 1500 amperes at 50 volts on the basis of continuous operation. They are driven by 125-hp, 600 rpm, unity power factor, synchronous

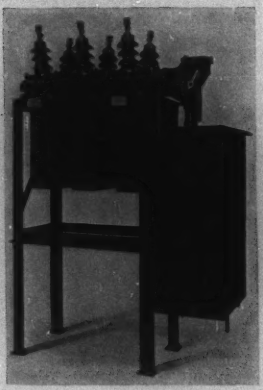
motors. The automatic control consists essentially of a Ward Leonard motor driven field rheostat and timer and Roller-Smith graphic recording ammeter and voltmeter.

Tripping Element for Air-Breakers.—A new thermal tripping element for motor-starting applications has been developed by the General Electric Co., Schenectady, N. Y.,

for use with type AE-1 industrial air circuit breakers. The new unit consists of a magnetically operated tripping mechanism which is restrained from tripping on overcurrent by means of a bimetallic element having thermal characteristics suitable for the starting and running protection of a-c motors. This bimetallic unit, heated inductively from the magnetic circuit of the overcurrent tripping device, releases the armature of this device when the proper tripping temperature is reached. Means of calibration of the mechanism have been provided to raise or lower the tripping point as desired. On overcurrents exceeding 10 times normal, the pull of the magnetic element acts independently of the thermal restraint, and instantaneous tripping occurs.

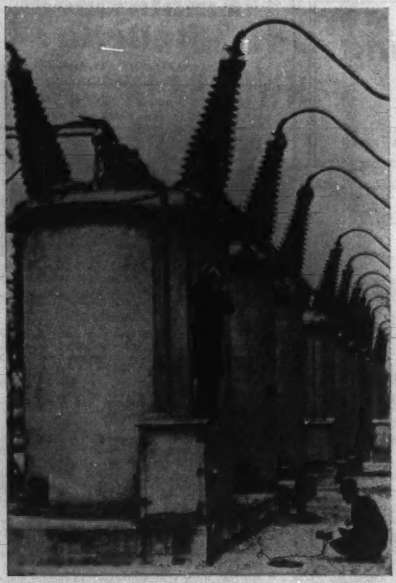
Miniature Transformers.—Ferranti Electric, Inc., 30 Rockefeller Plaza, New York City, announces a complete line of miniature transformers, known as the AERO series, particularly applicable in the communications and electronics fields, as they are not only light in weight but extremely small in size. They are ideal for aircraft and other portable, compact installations. Overall dimensions, including reversible mounting arrangements are $1\frac{1}{4}$ by $1\frac{1}{2}$ by $1\frac{1}{2}$ inches high. The latest nickel alloys are used as core materials and coils are of moisture-proof construction for use in marine and aeronautical service. Transformers have a usable range of from 20 to 20,000 c.p.s., and are available in input, interstage, output, bridging and mixing types; operating level ranges from minus 80 to plus 22 db., and a special group is included which is capable of passing plate current when used over the voice range.

Oil Circuit Breaker.—A new, moderate capacity, outdoor oil circuit breaker of the quick-clearing, non-oil-throwing design, known as type OZ-110, has been introduced by the Allis-Chalmers Manufacturing Co., Condit Works, Boston. Special interrupting devices called Ruptors are used to give quick clearing of short circuits, low arc energy, low pressure and minimum of oil



deterioration. Other features include: rigid cast steel top frames; silver contact surfaces; low-inertia, straight-line-motion type mechanisms; high speed operator; roomy, weatherproof control cabinet; one-piece, wet process porcelain bushings. The breaker is furnished for 600 amperes at 15 kv, with an interrupting capacity of 100,000 kv; for pole or frame mounting.

Small-Size Phototube.—The latest addition to the G-M Vistron line of phototubes is type 62A, a small unit only two inches high. It has all the performance characteristics of larger G-M types and is especially adapted to small size apparatus. Dimensions are: overall height (not including prongs) 2 inches; bulb diameter $\frac{7}{8}$ inches; sensitive plate height $\frac{1}{4}$ inches; plate width $\frac{5}{8}$ inches; distance from bottom of base to center of sensitive plate $1\frac{1}{2}$ inches. The new phototube is a product of G-M Laboratories, Inc., Chicago.



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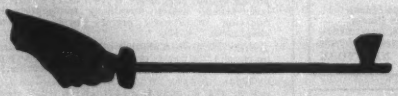

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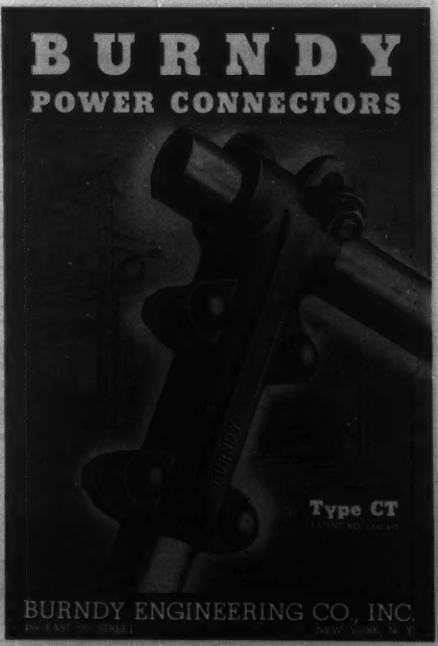

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Employers interested in the following announcements should address replies to the key numbers indicated, and mail to the New York office.

Men Available

E.E., Univ grad; 20 yrs pub util; des, oprn; pwr stations, substations transm, distr; 2 yrs inventory, appraisal. State license. Desires pos with util or indus firm. E-165.

E.E., B.S., '23, married, age 37. Exec util. Exper steam, hydro, constr, transm, reports; 18 yrs exper in mgmt, personnel and pub relations. Employed at present. E-163.

PWR SALES EXEC, E.E., 25 yrs with util; exper in private plant economy studies, difficult negotiations, especially competitive; 10 yrs as mgr pwr sales. Desires similar pos. E-164.

E.E. with exec, devpmt, prod, des exper with large mfr, lightning protective and X-ray apparatus, desires pos with util or mfr in responsible engr or sales engg capacity. E-169.

ENGG EXEC, age 44, married, Am. born; over 20 yrs diversified engg exper project planning, des, constr, estimating, cost analysis and valuation. Licensed Prof Engr N Y State; willing to travel. E-172.

E.E., M.E., N Y State license; 25 yrs des, constr, pwr houses, substations, distr system, industrial plants, elec RR; exec engg dept large util. Purchased engg eqpt foreign interest. English, German, Russian, Oriental languages. E-171.

RECENT GRAD, B.S.E.E., '36, Univ Penn, M.S.E.E., 1937, Univ Mich. Single. Specialized in pwr engg. Exper: Substn design. Desires pos with util or mfg concern. Location immaterial. Available on notice. E-174.

E.E., B.S., 1936, 29, married. Presently employed in elec. engg field; 6 yrs lt and pwr util and com exper; salary secondary to opportunity. Location immaterial, prefers foreign contract assignment. E-175.

E.E., '37 grad, Yale Sch of Engg; 2 mos exper on transm line constr crew. Interested in any pos in pwr and indus end of elec engg. Location immaterial. E-159.

E.E., B.E.E., Poly Inst of Brooklyn, 1937, single, 23; at present pursuing M.S. in E.E. at Poly (evening); prefers des or research. Location, N Y or commuting distance. Available immed. E-160.

B.S., E.E., 1936, Cooper Union, single, 24. Excellent ref. Has business training. Desires junior engg pos or one leading to sales. Salary, location secondary to advancement. May I have an interview? E-161.

GRAD B.E.E., Poly Inst of Brooklyn, 1937, single, 23; exper in radio service work. Desires pos as E.E. in com or electronic field. Will go anywhere. E-162.

E.E., B.S., 1937 honor grad; 2 yrs exper involving relay testg, maintenance, draftg and X-ray devpmt. Testg, devpmt or constr. work desired. Location immaterial. Salary secondary. E-166.

GRAD E.E., 1937, HEN, now employed, single, 24; 1½ yrs laminated phenolic lam. lab, 1½ yrs pwr house boiler room, ½ yr elec test small transf, control units. Foreign language, German. E-167.

B.S., '36, M.E.E. '37, 23; one yr instructional staff of large tech sch; 3 yrs tutoring basic engg courses; some practical exper. Desires: Teaching, research or junior engg pos. E-173.

B.E.E. Magna Cum Laude '34, evening grad work to date; 8 mos' exper naval control instruments; 30 mos' exper vacuum tube research, lab eqpt des and maintenance, administration. Available immed. E-168.

E.E. GRAD, 1929, Prof Engr, 29; appliance and pwr sales exper; knowledge of and exper with distr systems. Desires managerial, organizing, exec sales pos, preferably with util or mfr. E-170.

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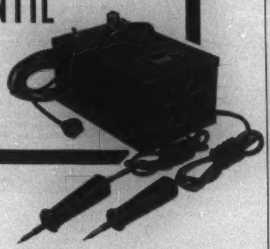

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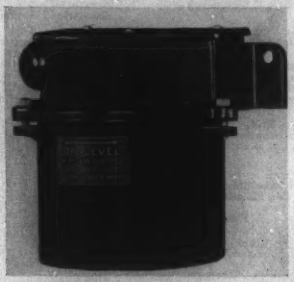

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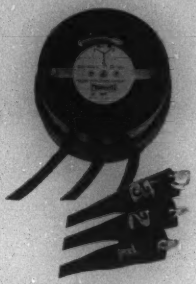
*The figure 19,000,000 is for the United States only. The total becomes 35,000,000 when you add the overseas telephone connections of the Bell System.



FERRANTI PHASE ROTATION INDICATOR

Indispensable where metering equipment is involved in 3-phase supply.

The Ferranti Phase Rotation Indicator is provided with insulated clips numbered, 1, 2 and 3 which distinguish phase to which they should be attached. Direction of disc rotation tells immediately if phase rotation is correct. Invaluable also for correctly marking bus bars and leads.

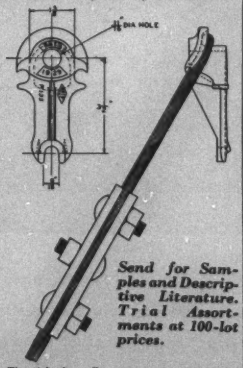
Send for complete descriptive data

FERRANTI ELECTRIC, Inc. 30 Rockefeller Plaza New York, N. Y.

M. I. F. Through-bolt Guying Specialties

Led by the M. I. F. Through-bolt Guy Hooks, these Guying Specialties are now being used from Maine to California and from Canada to Mexico, with relatively few gaps, by the leading Light and Power Companies. They are specified also for R. E. A. guying.

Guy Hooks—The P 135 type illustrated is for R. E. A. projects and other light construction. Rated for 13,000 lb. strand on 5/8" through-bolt. Priced at $15.60/C, F. O. B. Branford, and *lower in quantity*. P 134 Guy Hook for mounting on crossarm is rated at 10,000 lbs. as there is no supporting lag. Larger P 133 Guy Hook, rated at 16,000 lbs. on 5/8" bolt and at 20,000 lbs. on 3/4" bolt, is type of most universal application. Still larger P 132 Guy Hook, rated at over 35,000 lbs. on 1" bolt may be installed with second through-bolt, thereby increasing capacity. Sometimes used for two 3/8" guys at corners. Where stresses are placed on poles by attachments to through-bolts, then the same through-bolts should logically be used for attaching the guys by means of Guy Hooks.



Send for Samples and Descriptive Literature. Trial Assortments at 100-lot prices.

Eye Nuts and Anchor Rods—P 128 Thimbleless 5/8" Eye Nut now priced at $12.60/C is being used by most Companies using these Guy Hooks. Also furnished assembled on high-strength steel rods as Thimble-less Eye Bolts and Anchor Rods at attractive prices. Larger sizes, Bolt Eyes, and Double Eye Nuts also available.

Curved Washers—The most complete line available anywhere from P 143, 3" x 3" at $6.60 /C up to P 119, 6" x 6" at $42.00/C. *All prices lower for larger quantities.*

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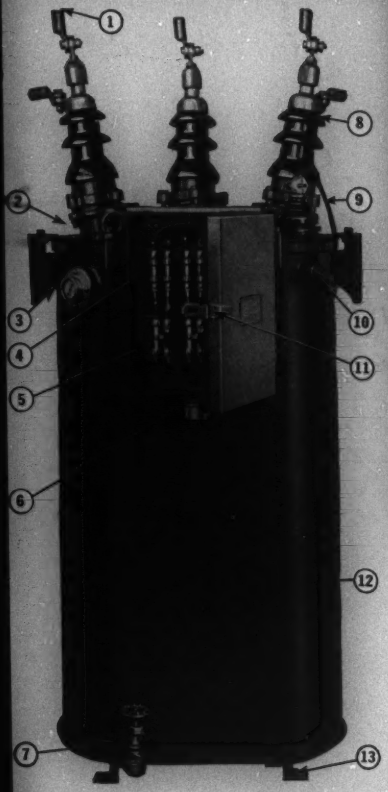

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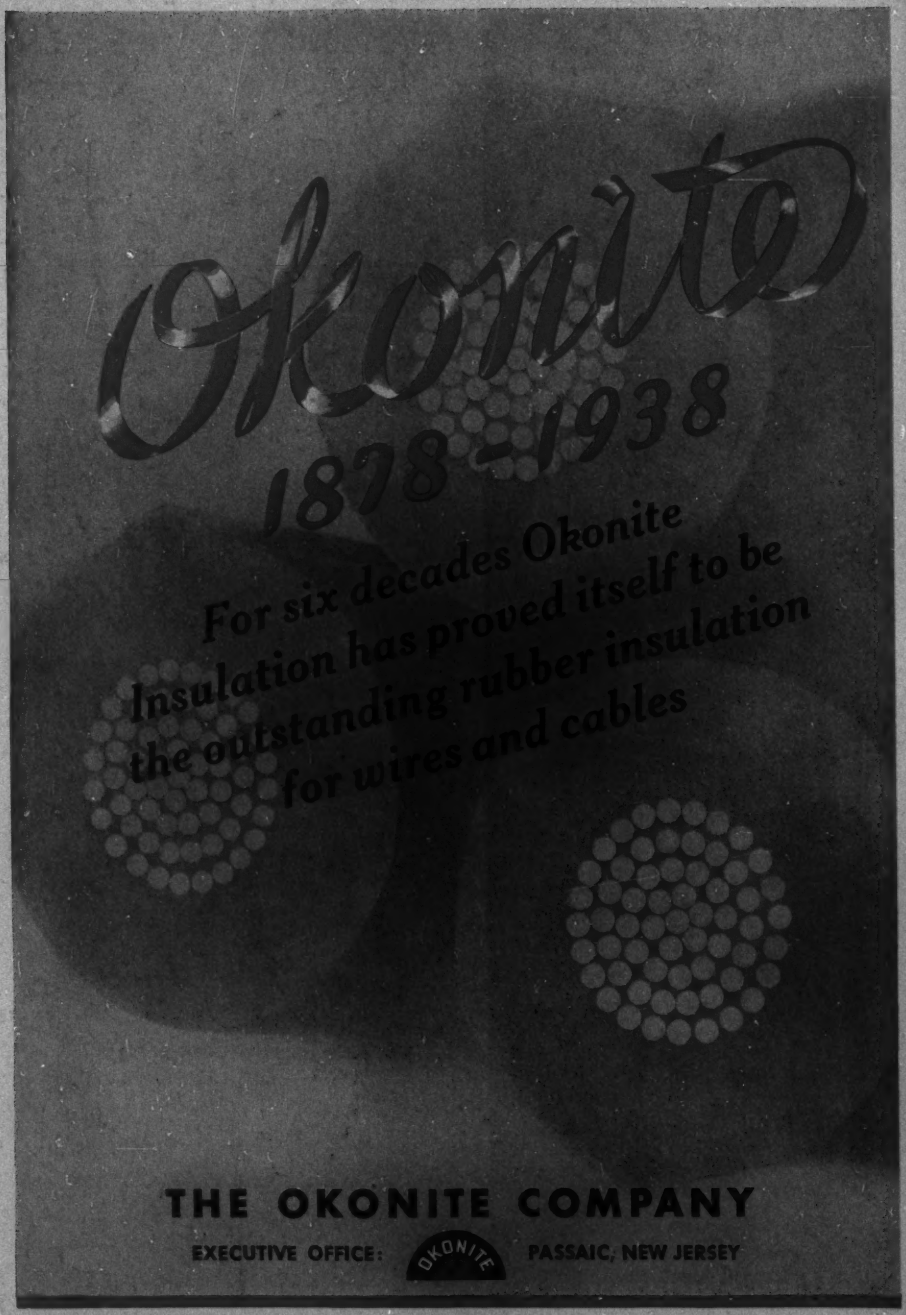
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